

MHD study of extreme space weather conditions for exoplanets with Earth-like magnetospheres: On habitability conditions and radio-emission

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Abstract

The present study aims at characterizing the habitability conditions of exoplanets with an Earth-like magnetosphere inside the habitable zone of M and F stars, caused by the direct deposition of the stellar wind on the exoplanet surface. Also, the radio emission generated by exoplanets with a Earth-like magnetosphere is calculated for different space weather conditions. The study is based on a set of MHD simulations performed by the code PLUTO. Exoplanets hosted by M stars at 0.2 au are protected from the stellar wind during regular and CME-like space weather conditions if the star rotation period is slower than 3 days. Exoplanets hosted by a F stars at ≥ 2.5 au are protected during regular space weather conditions, but a stronger magnetic field compared to the Earth is mandatory if the exoplanet is close to the inner edge of the star habitable zone (2.5 au) during CMEs. The range of radio emission values calculated in the simulations are consistent with the scaling proposed by [Zarka](#) during regular and common CME-like space weather conditions. If the radio telescopes measure a relative low radio emission signal with small variability from an exoplanet, that may indicate favorable exoplanet habitability conditions. The radio emission power calculated for exoplanets with an Earth-like magnetosphere is in the range of $3 \cdot 10^7$ to $2 \cdot 10^{10}$ W for SW dynamic pressures between 1.5 to 100 nPa and IMF intensities between 50 - 250 nT, and is below the sensitivity threshold of present radio telescopes at parsec distances.

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2 **with Earth-like magnetospheres: On habitability conditions and**
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12 **Key Points:**

- 13 • Space weather
14 • Habitability conditions
15 • Radio emission
16 • M stars
17 • F stars

Abstract

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Plain Language Summary

Space weather conditions the habitability of exoplanets hosted by M and F stars leading to the direct deposition of the stellar wind towards the exoplanet surface, particularly if the exoplanet orbit is located in the inner part of the habitable zone and it is exposed to frequent coronal mass ejections. The analysis of the radio emission generation in exoplanets with an Earth-like magnetosphere indicates the important role of the bow shock compression, not correctly reproduced by theoretical scalings. In addition, for exoplanet facing a stellar wind in the sub-Afvénic regime (the magnetic pressure of the interplanetary magnetic field is dominant and the bow shock disperses), the radio emission generation may show large fluctuations caused by the variability of the interplanetary magnetic field orientation.

1 Introduction

The space weather effects on the Earth magnetosphere were extensively studied in the last years (Poppe, B.B. & Jordan, K.P., 2006; González Hernández, I. et al., 2014; Varela, J. et al., 2022), particularly during extreme events such as intense coronal mass ejections (CME) (Low, B. C., 2001; Howard, R.A., 2006) leading to major perturbations in the Earth magnetosphere structures (Wang, Y. M. et al., 2003; Lugaz, N. et al., 2015; Wu, C. & Lepping, R. P., 2015).

The CMEs are solar eruptions produced in the corona due to magnetic reconnections, expelling fast charged particles and a magnetic cloud (Neugebauer & Goldstein, 1997; Cane, H. V. & Richardson, I. G., 2003; Regnault, F. et al., 2020). Extreme space weather events are not exclusive of the Sun or solar-like stars (Leitzinger et al., 2020), CMEs were also observed in M, K and F type stars (Khodachenko et al., 2007; Lammer et al., 2007).

The space weather at the orbit of the Earth and exoplanets depends on the stellar wind (SW) and interplanetary magnetic field (IMF) generated by the host star (Strugarek et al., 2015; Garraffo, C. et al., 2016) at their orbital location as well as the conducting and magnetic properties of the local environment. For the case of the Earth, the intrinsic magnetic field is strong enough to avoid the direct precipitation of the SW on the surface even during the largest CMEs observed (Salman, T. M. et al., 2018; Kilpua, E.K.J. et al., 2019; Hapgood, M., 2019). Extreme space weather conditions occur if the SW dynamic pressures in the range of the 10 to 100 nPa and IMF intensity between 100 and 300 nT.

65 The space weather in the orbit of exoplanets cannot be compared to the case of the Earth
 66 if the host star has characteristics different from the Sun (star type, age, metallicity, ...). If the SW
 67 dynamic pressure and IMF intensity generated by the star are large, favorable exoplanet habit-
 68 ability state requires an intrinsic magnetic field strong enough to avoid the direct precipitation
 69 of the SW on the exoplanet surface (Gallet, F. et al., 2017; Linsky, J., 2019; Airapetian, V. S. et
 70 al., 2020). Otherwise, if the protection of the magnetic field is deficient, the exoplanet habitabil-
 71 ity can be hampered by the effect of the SW as well as the depletion of the atmosphere, especially
 72 volatile components such as the water molecules (Lundin, R. et al., 2007; Moore, T. E. & Khaz-
 73 anov, G. V., 2010; Jakosky, B. M. et al., 2015). It should be noted that other important factors for
 74 the habitability as EUV, X ray and cosmic rays fluxes towards the exoplanet surface are not in-
 75 cluded in the analysis as such effects are beyond the scope of the present study. Nevertheless, the
 76 eventual direct precipitation of the SW must be understood as an important constraint for the hab-
 77 itability of planets.

78 Exoplanet habitability could be constrained for exoplanet without an intrinsic magnetic field,
 79 although the detection and characterization of exoplanet magnetospheres is a challenging topic.
 80 It is known from the interaction of the SW with the planets of the solar system that intrinsic mag-
 81 netic fields are emitters of cyclotron MASER emission at radio wavelengths (Kaiser & Desch,
 82 1984; Zarka, 1998; Lamy et al., 2017), generated by energetic electrons accelerated in the recon-
 83 nection region between IMF and the planet magnetic field, flowing towards the planet surface
 84 along the magnetic field lines (Wu, 1979). A fraction of the electrons energy is transformed into
 85 cyclotron radio emission (Zarka, 1998) escaping from the magnetosphere. Such radio emission
 86 is detected by ground-based radio telescopes, for example the Nançay decameter array (Lamy
 87 et al., 2017), NenuFAR (Zarka et al., 2020) and Low Frequency Array (LOFAR) (van Haarlem,
 88 M. P. et al., 2013) between others. Likewise, the radio emission detected from an exoplanet mag-
 89 netosphere could provide information of the exoplanet intrinsic magnetic field (Hess & Zarka,
 90 2011). Unfortunately, the detection capability of present radio telescopes barely distinguish the
 91 radio emission from exoplanets. Recent LOFAR and the Australian Telescope Compact Array
 92 (ATCA) measurements tentatively achieved the detection of radio emission from exoplanet sys-
 93 tems (Turner, J. D. et al., 2021; Pérez-Torres, M. et al., 2021). In addition, radio emission from
 94 the red dwarf GJ 1151 was measured, potentially originated in the magnetic interaction with a ex-
 95 oplanet with approximately the size of the Earth (Vedantham, H. K. et al., 2020; Benjamin J. S.
 96 et al., 2020; Perger, M. et al., 2021). Next generation of radio telescopes may be able to detect
 97 exoplanet radio emissions at a distances of 20 parsec (Carilli & Rawlings, 2004; Nan et al., 2011;
 98 Ricci et al., 2018; Zarka et al., 2020), for example the Square Kilometre Array (SKA) (Zarka et
 99 al., 2015), depending on the space weather conditions generated by the host star and the prop-
 100 erties of the exoplanet magnetic field.

101 This study is the continuation of a research activity dedicated to analyze numerically the
 102 interaction of the stellar wind with planetary magnetospheres, particularly the radio emission gen-
 103 eration with respect to the space weather conditions and the properties of the planet intrinsic mag-
 104 netic field. First, the radio emission from the Hermean magnetosphere was analyzed in Varela,
 105 Reville, et al. (2016), showing the important role of the IMF intensity, IMF orientation and SW
 106 dynamic pressure on the radio emission generated. Then, Varela, J. et al. (2018) was dedicated
 107 to study the radio emission from exoplanets with different intrinsic magnetic field configurations,
 108 identifying a critical dependency between magnetosphere topology and radio emission. Next,
 109 Varela, J. et al. (2022) analyzed the effect of extreme space weather conditions on the Earth mag-
 110 netosphere. The aim of the present study is to analyze the effect of the space weather conditions
 111 on the magnetosphere of exoplanets orbiting the habitable zone of M and F stars. In addition, the
 112 radio emission generated from the exoplanet magnetosphere is estimated. The analysis consist
 113 in a set of MHD simulations assuming the exoplanet magnetic field is identical to the Earth mag-
 114 netic field, reproducing the space weather conditions inside the habitable zone of M and F stars.

115 This paper is structured as follows. Section 2 presents the description of the numerical model.
 116 Section 3 introduces the analysis of the space weather effects on the magnetosphere of exoplanet
 117 orbiting the habitable zone of M and F stars. Section 4 presents the characterization of the ra-

118 dio emission generated by exoplanets with an Earth-like magnetosphere during extreme space
119 weather conditions. Section 5 discusses and concludes the analysis results.

120 2 Numerical model

121 This study is performed using the ideal MHD version of the open-source code PLUTO in
122 spherical coordinates. The model calculates the evolution of a single-fluid polytropic plasma in
123 the nonresistive and inviscid limit (Mignone et al., 2007). A detailed description of the model
124 equations, boundary conditions and upper ionosphere model can be found in (Varela, J. et al., 2022).

125 The interaction of the SW with planetary magnetospheres can be studied using different
126 numerical models; present study uses a single fluid MHD code (Kabin et al., 2008; Jia et al., 2015;
127 Varela et al., 2015; Strugarek et al., 2014, 2015). The validity of MHD code results were checked
128 by comparing the simulation results with ground-based magnetometers and spacecraft measure-
129 ments (Watanabe, K. & Sato, T., 1990; Raeder, J. et al., 2001; Wang, Y. L. et al., 2003; Facskó,
130 G. et al., 2016). The study was performed using the single-fluid MHD code PLUTO in spher-
131 ical 3D coordinates (Mignone et al., 2007). The model was applied successfully to study the global
132 structures of the Hermean magnetosphere (Varela et al., 2015; Varela, Pantellini, & Moncuquet,
133 2016b, 2016c, 2016a; Varela, Reville, et al., 2016), the radio emission from exoplanets (Varela,
134 J. et al., 2018) and the effect of extreme space weather conditions on the Earth magnetosphere
135 (Varela, J. et al., 2022).

136 The simulations use a grid of 128 radial points, 48 in the polar angle θ and 96 in the az-
137 imuthal angle ϕ , equidistant in the radial direction. The simulation domain is confined between
138 two concentric shells around the exoplanet, with the inner boundary $R_{in} = 2R_{ex}$ (R_{ex} the exo-
139 planet radius) and the outer boundary $R_{out} = 30R_{ex}$. The upper ionosphere model extends be-
140 tween the inner boundary and $R = 2.5R_{ex}$.

141 The exoplanet magnetic field is rotated 90° in the YZ plane with respect to the grid poles
142 with the aim of avoiding numerical issues (no special treatment was included for the singular-
143 ity at the magnetic poles). The exoplanet magnetosphere is identical to the Earth magnetosphere,
144 thus the tilt of the Earth rotation axis is also included (23° with respect to the ecliptic plane).

145 The simulation frame assumed is: z-axis is provided by the planetary magnetic axis point-
146 ing to the magnetic north pole, star-planet line is located in the XZ plane with $x_{star} > 0$ (solar
147 magnetic coordinates) and the y-axis completes the right handed system.

148 The response of the exoplanet magnetosphere for different SW dynamic pressure (P_d), IMF
149 intensity ($|B|_{IMF}$) and orientation is calculated based on the data regression obtained by the set
150 of simulations performed in Varela, J. et al. (2022) (see Table 5). The SW dynamic pressure is
151 defined as $P_d = m_p n_{sw} v_{sw}^2 / 2$, with m_p the proton mass, n_{sw} the SW density and v_{sw} the SW ve-
152 locity.

153 The effect of different IMF orientations are included in the analysis: Exoplanet-star and
154 star-exoplanet (also called radial IMF configurations), southward, northward and ecliptic clock-
155 wise. Exoplanet-star and star-exoplanet configurations indicate an IMF parallel to the SW ve-
156 locity vector. Southward and northward IMF orientations show an IMF perpendicular to the SW
157 velocity vector in the XZ plane.

158 3 Magnetopause standoff distance for exoplanets with an Earth-like magnetic field

159 This section is dedicated to calculate the magnetopause standoff distance of exoplanets with
160 an Earth-like magnetic field exposed to different space weather conditions. A detailed descrip-
161 tion of the standoff distance calculation in the simulations is shown in the appendix. The anal-
162 ysis includes regular and CME-like space weather conditions expected for exoplanet orbiting in-
163 side the habitable zone of M and F stars. Consequently, the study provides a first order assess-
164 ment of the exoplanet habitability with respect to the SW direct deposition on the exoplanet sur-

face. The analysis is performed assuming exoplanets with an Earth-like magnetic field because no observational data exists regarding the properties of exoplanets magnetosphere. Nevertheless, the different IMF orientations tested are equivalent to exoplanets with different tilt angles.

The space weather conditions inside the stellar habitable zone change with the star characteristics (Kasting, J. F. et al., 1993; Tarter, J. C. et al., 2007; Kopparapu, R. K. et al., 2013; Johnstone, C. P., Güdel, M., Brott, I., & Lüftinger, T., 2015; Cuntz, M. & Guinan, E. F., 2016; Airapetian, V. S. et al., 2020). The habitable zone for main sequence F stars ($1.1 - 1.5M_{Sun}$) is located between 2.5 - 5 au (Sato, S. et al., 2014), G stars ($1.1 - 0.9M_{Sun}$) between 0.84 - 1.68 au (Kopparapu, R. K. et al., 2014), K stars ($0.9 - 0.5M_{Sun}$) between 0.21 - 1.27 au (Cuntz, M. & Guinan, E. F., 2016) and M stars ($< 0.5M_{Sun}$) between 0.03 - 0.25 au (Shields, Aomawa L. et al., 2016). In the following, the habitability conditions imposed by the star in exoplanets at different orbits inside the habitable zone of M and F stars are studied.

The habitability conditions obtained in the simulations are defined with respect to the magnetopause standoff distance above the exoplanet surface. If the normalized standoff distance is $R_{mp}/R_{ex} = 1$ (R_{mp} is the exoplanet magnetopause standoff distance) there is a direct precipitation of the SW towards the exoplanet surface. This is the same criteria used in Varela, J. et al. (2022) (equations 5 and 6).

3.1 Exoplanet hosted by M stars

M type stars habitability conditions are an open issue because exoplanets inside the habitable zone are likely to be tidally locked (Grießmeier, J.-M. et al., 2004, 2005) and exposed to a strong radiation from the host star (Scalo, J. et al., 2007) as well as persistent CME events (Khodachenko et al., 2007; Lammer et al., 2007). Nevertheless, recent studies indicate tidal locking may constrain but not preclude the habitability conditions of exoplanets (Yang et al., 2013; Hu & Yang, 2014; Leconte et al., 2015; Barnes, 2017). Previous studies also assessed the space weather conditions in the orbit of exoplanets inside the habitable zone of M stars (Odstrcil, D. & Pizzo, V. J., 1999; Odstrcil, D. et al., 2004; Vidotto, A. A. et al., 2013). Table 1 shows the density, velocity and dynamic pressure of the SW generated by a M star at different orbits following Johnstone, C. P., Güdel, M., Lüftinger, T., et al. (2015) SW model for regular and CME-like space weather conditions. The CME-like space weather conditions are guess educated values assuming 20 times the SW density and 2.5 times the SW velocity of the regular space weather conditions. Such parameters are typical for CME conditions for the Sun.

Figure 1 shows the exoplanet habitability constrain imposed by the space weather conditions inside the habitable zone of a M star. The graphs indicate the critical IMF intensity and SW dynamic pressure required for the direct SW precipitation towards the exoplanet surface in the equatorial region (for different IMF orientations), that is to say, the space weather conditions leading to a normalized exoplanet magnetopause standoff distance of $R_{mp}/R_{ex} = 1$. It should be noted that the graphs show the data regression obtained by the simulation performed in Varela, J. et al. (2022), dedicated to calculate the Earth magnetopause standoff distance for different values of the SW dynamic pressure, IMF intensities and IMF orientations. The range of SW dynamic pressure and IMF intensity values included in the study correspond to regular (panel a) and CME-like (panel b) space weather conditions. The horizontal dashed lines indicate the SW dynamic pressure at the orbit of an exoplanet at 0.05 au (red), 0.1 au (orange) and 0.2 au (blue) from the host star based on Johnstone, C. P., Güdel, M., Lüftinger, T., et al. (2015) SW model, providing a reference value of the critical IMF intensity required for the direct SW precipitation onto the exoplanet surface for different IMF orientations based on the pressure balance (see appendix).

During regular space weather conditions, panel a, the critical IMF intensity for an exoplanet at 0.2 au is $|B|_{IMF} > 5000$ nT, ≈ 2050 nT at 0.1 au and ≈ 1100 nT at 0.05 au if the IMF is southward. The southward IMF is highlighted along the article because it is the IMF orientation leading to the lowest magnetopause standoff distance (maximum reconnection) for a fixed IMF intensity. Consequently, the magnetic field generated by M stars must be very large to threaten the exoplanet habitability. Nevertheless, the magnetic field of young and fast rotating M stars can

Regular SW			
AU	n_{sw} (cm^{-3})	$ v_{sw} $ (km/s)	P_d (nPa)
0.05	2000	540	488
0.1	500	650	177
0.2	90	700	37
CME-like SW			
AU	n (10^3 cm^{-3})	$ v $ (km/s)	P_d (10^3 nPa)
0.05	40	1350	61
0.1	10	1650	23
0.2	1.8	1750	4.6

Table 1. Exoplanet orbit inside the habitable zone of M stars (first column). SW density (second column), velocity (third column) and dynamic pressure (fourth column) for regular and CME-like space weather conditions.

216 overcome such IMF intensity thresholds (Shulyak, D. et al., 2017, 2019) reaching values up to
 217 4 kG. The IMF intensity threshold during a CME largely decreases compared to regular space
 218 weather conditions, panel b. If the exoplanet orbit is at 0.2 au, the critical $|B|_{IMF} \approx 310$ nT for
 219 a southward IMF and ≈ 1100 nT for a star-exoplanet IMF. If the exoplanet is at 0.1 au, $|B|_{IMF} \approx$
 220 110 nT for a southward IMF, ≈ 500 nT for a star-exoplanet IMF and ≈ 3750 nT for a northward
 221 IMF. If the exoplanet is at 0.05 au, $|B|_{IMF} \approx 60$ nT for a southward IMF, ≈ 325 nT for a star-
 222 exoplanet IMF and ≈ 2100 nT for a northward IMF. That is to say, exoplanets at 0.2 au are effi-
 223 ciently protected during CME space weather conditions if the intensity of the magnetic field
 224 generated by the M star is not strong enough to exceed 310 nT. On the other hand, exoplanets
 225 at ≤ 0.1 au are exposed to the direct SW precipitation during CMEs if the IMF intensity exceeds
 226 110 nT. In summary, exoplanets at 0.2 au should be protected from the direct precipitation of the
 227 SW by an Earth-like magnetic field, thus the exoplanets is habitable with respect to the SW shield-
 228 ing. It should be noted that present study conclusions are consistent with respect to configura-
 229 tion subsets analyzed by other authors (Garraffo, C. et al., 2016, 2017).

230 As it was mentioned in the previous paragraph, the space weather conditions change with
 231 the rotation rate of the star, because the magnetic activity and the properties of the SW generated
 232 by the star change (Suzuki, T.K., 2013). The SW velocity during regular space weather condi-
 233 tions is 2 times larger if the star rotation is 4 times faster, although the SW density and temper-
 234 ature is weakly affected (Shoda, M. et al., 2020). In addition, faster rotators have a stronger mag-
 235 netic activity, because the large-scale surface magnetic field ($B_{surf,*}$) dependency with the Rossby
 236 number (R_o) is $B_{surf,*} \propto R_o^{-1.3}$ (See, V. et al., 2019; Brun, A. S. et al., 2022). Thus the IMF in-
 237 tensity at the exoplanet orbit is higher as well as the CME frequency and intensity (Shulyak, D.
 238 et al., 2017, 2019). Consequently, if the effect of the M star rotation period is included in the anal-
 239 ysis, the threshold of the IMF intensity and SW dynamic pressure for the direct precipitation of
 240 the SW toward the exoplanet surface changes. Table 2 indicates the SW density and velocity in
 241 the orbit of an exoplanet at 0.05, 0.1 and 0.2 au from the host M star for different rotation peri-
 242 ods (P_{rot}) for the star during regular space weather conditions (data derived from Shoda, M. et
 243 al. (2020) simulations). The SW density has a weak dependency with the star rotation but the SW
 244 velocity and IMF intensity increases with the star rotation. The range of M star rotation periods
 245 analyzed include the majority of the 795 M stars identified by Kepler mission as a sub-sample
 246 of the 12000 main sequence stars identified (Nielsen, M. B. et al., 2013). Nevertheless, recent
 247 surveys of M star identified an important population of slow M stars rotators, showing rotation
 248 periods between 30 to 120 days (Newton, E. R. et al., 2018; Popinchalk, M. et al., 2021).

AU	P_{rot} (days)	n_{sw} (cm^{-3})	$ v_{sw} $ (km/s)	P_d (nPa)	$ B _{IMF}$ (10^3 nT)
0.05	24	4500	280	295	2.16
0.05	12	4500	360	488	17.7
0.05	6	4500	400	602	25.9
0.05	3	4500	450	762	30.3
0.1	24	900	350	92.2	0.54
0.1	12	900	440	146	4.43
0.1	6	900	510	196	6.46
0.1	3	900	620	289	7.57
0.2	24	240	410	33.7	0.31
0.2	12	240	500	50.2	1.11
0.2	6	240	590	69.9	1.62
0.2	3	240	800	128	1.89

Table 2. Exoplanet orbit inside the habitable zone of M stars (first column). Star rotation period (second column). SW density (third column), velocity (forth column) and dynamic pressure (fifth column). IMF intensity (sixth column).

249 Figure 2 indicates the IMF intensity and SW dynamic pressure threshold with respect to
250 the M star rotation rate for regular space weather conditions.

251 The model shows a large decrease of the IMF intensity threshold if the M star rotation pe-
252 riod decreases given a SW dynamic pressure. $\Delta|B|_{IMF}$ is indicated by the bold arrows in the top
253 of the graph for each IMF orientation between the cases of star with rotation rates of 24 and 3
254 days. For an exoplanet at 0.05 au, the IMF intensity threshold decreases from 1500 nT to 850 nT
255 reducing the star rotation period from 24 to 3 days if the IMF is southward, as well as from 3000
256 nT to 2000 nT if the IMF is in the exoplanet-star orientation. Regarding an exoplanet orbit at 0.1
257 au, the IMF intensity threshold decreases from 3250 nT to 1500 nT for a southward IMF, as well
258 as from 4750 nT to 3000 nT for an exoplanet-star IMF. If the exoplanet orbit is located at 0.2 au,
259 the IMF intensity threshold decreases from 5550 nT to 2600 nT for a southward IMF and from
260 7000 nT to 4250 nT for an exoplanet-star IMF. The IMF intensity threshold obtained can be com-
261 pared with the magnetic field generated by M stars at different orbits following Shoda, M. et al.
262 (2020) simulations (last column of table 2). At 0.05 au, the IMF intensity is above the threshold
263 for a Southward IMF orientation if the star rotation period is shorter than 24 days, and below the
264 threshold for an exoplanet-star IMF if the rotation period is 24 days or larger. That is to say, fa-
265 vorable habitability conditions with respect to SW of an exoplanet at 0.05 au require an intrin-
266 sic magnetic field stronger than Earth's if the rotation rate of the M star is 24 days or smaller. At
267 0.1 au, the IMF intensity is above the threshold for Southward and exoplanet-star IMF orienta-
268 tion and the rotation rate is 12 days or faster. Thus, exoplanets at 0.1 au require a magnetic field
269 stronger than the Earth if the host M star rotation rate is smaller than 12 days. If the exoplanet
270 is at 0.2 au, the IMF intensity is below the threshold for all IMF orientations if the star rotation
271 rate is 3 days or slower, so an Earth-like magnetic field can efficiently shield the exoplanet sur-
272 face.

273 Summarizing, exoplanets with an Earth-like magnetic field hosted by a M star and located
274 at 0.2 au are shielded from the SW during regular and CME-like space weather conditions. In
275 addition, such protection holds for M stars with rotation periods as fast as 3 days during regu-
276 lar SW space weather conditions. Nevertheless, fast rotating M stars with strong and recurrent
277 CME-like events can restrict the exoplanet habitability conditions. On the other hand, exoplan-
278 ets at 0.1 au are shielded from regular and CME-like space weather conditions only if the M stars
279 rotation period is 12 days or larger. Finally, exoplanets at 0.05 are vulnerable during CME-like
280 events even for M stars with the a rotation period of 24 days, thus exoplanet habitability requires

Regular SW			
AU	n_{sw} (cm^{-3})	$ v_{sw} $ (km/s)	P_d (nPa)
2.5	50	300	3.8
5.0	20	310	1.6
CME-like SW			
AU	n (10^3 cm^{-3})	$ v_{sw} $ (10^3 km/s)	P_d (10^3 nPa)
2.5	1.0	1.5	1.88
5.0	0.4	1.55	0.8

Table 3. Exoplanet orbit inside the habitable zone of F star type τ Boo (first column). SW density (second column), velocity (third column) and dynamic pressure (fourth column) for regular and CME-like space weather conditions.

281 a magnetic field stronger with respect to the Earth. Nevertheless, exoplanet at 0.05 au hosted by
 282 slower rotators with $P_{rot} > 24$ days are protected during standard and CME-like events by an
 283 Earth-like magnetic field if the IMF intensity is lower than 1000 nT for a southward IMF.

284 3.2 Exoplanet hosted by F stars type τ Boo

285 Space weather conditions in F stars were analyzed in previous studies, particularly for τ
 286 Boo type $F7V$, concluding the SW may have a density 135 times larger with respect to the SW
 287 generated by the Sun, as well as a velocity around 300 km/s (Vidotto et al., 2012). Table3 shows
 288 guess educated values of the space weather conditions in the orbit of an exoplanet hosted by a
 289 F star similar to τ Boo near the bottom and upper range of the habitable zone. The SW density
 290 during regular space weather conditions is assumed 100 times the SW density generated by the
 291 Sun at 2.5 and 5 au. The velocity is the same with respect to (Vidotto et al., 2012), 300 km/s at
 292 2.5 au. In addition, an extrapolation is assumed to characterize the space weather conditions dur-
 293 ing CMEs, selecting a SW density 20 times larger and a velocity 5 times higher with respect to
 294 the regular space weather conditions.

295 Figure 3 indicates the critical IMF intensity and SW dynamic pressure required for the di-
 296 rect SW precipitation towards an exoplanet hosted by a F star type τ Boo inside the habitable zone
 297 during CME-like space weather conditions. The same analysis for regular space weather con-
 298 ditions is not included because the IMF intensity and SW dynamic pressure are well below the
 299 threshold required for the direct SW precipitation, that is to say, the exoplanets at 2.5 – 5.0 au
 300 are shielded during regular space weather conditions.

301 Exoplanets located at 5 au show an IMF intensity threshold of $|B|_{IMF} \approx 825$ nT for a south-
 302 ward IMF and $|B|_{IMF} \approx 2300$ nT for an exoplanet-star IMF. Regarding exoplanets at 2.5 au, the
 303 IMF intensity threshold is $|B|_{IMF} \approx 500$ nT for a southward IMF and $|B|_{IMF} \approx 1550$ nT for an
 304 exoplanet-star IMF. It must be noted the magnetic activity of τ Boo is larger with respect to the
 305 Sun, showing a shorter magnetic cycle of 2 years (Fares, R. et al., 2009, 2013). It is known that
 306 F stars have a slower decrease of the rotation rate along the main sequence, leading to a stronger
 307 magnetic field compared to G stars (Saffe, C. et al., 2005; Mathur, S. et al., 2014) with the ex-
 308 ception of low mass stars populations ($< 0.9M_{Sun}$) that maintain rapid rotation for much longer
 309 than solar-mass stars (Matt, S. P. et al., 2015). Consequently, the effect of the CME on exoplan-
 310 ets orbiting inside the habitable zone of F star, particular τ Boo, can increase the exoplanet hab-
 311 itability conditions if the frequency of these extreme space weather events is high.

AU	P_{rot} (days)	n_{sw} (10^3 cm^{-3})	$ v_{sw} $ (10^3 km/s)	P_d (10^3 nPa)	$ B _{IMF}$ (10^3 nT)
2.5	2	1.0	1.7	2.4	3
2.5	5	1.0	1.3	1.4	1.5
2.5	7.5	1.0	1.15	1.1	1
2.5	10	1.0	1.0	0.8	0.5
5.0	2	0.4	1.75	1.0	0.75
5.0	5	0.4	1.35	0.6	0.4
5.0	7.5	0.4	1.2	0.5	0.25
5.0	10	0.4	1.05	0.4	0.1

Table 4. Exoplanet orbit inside the habitable zone of F star (first column). Star rotation period (second column). SW density (third column), velocity (forth column) and dynamic pressure (fifth column). IMF intensity (sixth column).

312 Next step of the analysis is to include the effect of stellar rotation. The F star rotation pe-
 313 riod is lower with respect to less massive stars such as G, K and M stars. The lower bound is around
 314 2 days for $F0$ stars increasing to 10 days for $F9$ stars (Nielsen, M. B. et al., 2013). Table 4 in-
 315 dicates guess educated values of the SW dynamic pressure and IMF intensity at different exo-
 316 planet orbits for different F star rotation periods during CME space weather conditions. The val-
 317 ues of the IMF intensity are extrapolated from observational data of F stars magnetic field mag-
 318 nitude (Bailey, J. D., 2014; Mathur, S. et al., 2014; Marsden, S. C. et al., 2014; See, V. et al., 2019;
 319 Seach, J. M. et al., 2020) and modeling results (Brun, A. S. et al., 2022). We assume the SW ve-
 320 locity increases with the star rotation although the SW density and temperature is constant, ex-
 321 trapolating Shoda, M. et al. (2020) results.

322 Figure 4 indicates the IMF intensity and SW dynamic pressure threshold with respect to
 323 the F star rotation rate for CME-like space weather conditions.

324 The simulations indicate the habitability of exoplanets at 2.5 au from the host F star is con-
 325 ditioned by the SW if the star rotation period is shorter than 10 days. The exoplanet surface is
 326 protected if the star rotation period is 10 days or above, showing an IMF intensity of 500 nT that
 327 is smaller compared to the IMF intensity required for the direct SW precipitation . For a stellar
 328 rotation of 7.5 or 5 days, direct SW precipitation exists during a southward IMF with 675 and
 329 575 nT, respectively, smaller than the IMF intensity during CMEs. The IMF threshold for the di-
 330 rect SW precipitation is also largely exceeded if the star rotation is 2 days for an IMF oriented
 331 in the Southward or Exoplanet-star directions. Consequently, exoplanets at 2.5 au requires an in-
 332 trinsic magnetic field intensity stronger with respect to the Earth if the star rotation period is smaller
 333 than 10 days. On the other hand, the simulations show that exoplanets with orbits at 5.0 au are
 334 protected during CME-like space weather conditions if the star rotation period is above 2 days.
 335 In the case of the rotation period is 2 days the IMF intensity threshold is similar to the IMF in-
 336 tensity during CMEs (around 25 nT smaller).

337 In summary, regular space weather conditions does not impact the habitability of exoplanets
 338 in the habitable zone of F stars type τ Boo. On the other hand, persistent and strong CME events
 339 can largely influence the habitability of exoplanets nearby the inner boundary of the habitable
 340 zone, thus a stronger magnetic field regarding the Earth magnetic field is mandatory. Neverthe-
 341 less, exoplanets at the outer region of the habitable zone could be efficiently shielded by an Earth-
 342 like magnetic field. The analysis of the star rotation effect on the habitability state due to the SW
 343 indicates that exoplanets with an Earth-like magnetic field at 5.0 au are efficiently protected dur-
 344 ing extreme space weather conditions if the star rotation period is larger than 2 days. On the other
 345 hand, exoplanets at 2.5 au requires an intrinsic magnetic field stronger regarding the Earth if the
 346 star rotation period is smaller than 10 days. It should be noted that the rotation period of τ Boo

347 is 3.3 days, thus habitability conditions due to the space weather require an exoplanet magnetic
 348 field stronger compared to the Earth. That means, habitability conditions may relax for the case
 349 of F stars in the spectral range from $F7$ to $F9$ because the rotation period is larger (10 days or
 350 higher) (Nielsen, M. B. et al., 2013). Nevertheless, the habitable zone of $F7$ to $F9$ stars displaces
 351 closer to the star, located between 1.1 to 2.5 au. Consequently, exoplanets located in the outer
 352 region of the habitable zone of $F7$ to $F9$ stars require, at least, a magnetic field similar to the Earth
 353 to avoid the direct SW precipitation during CMEs, although it must be stronger if the orbit is closer
 354 to the star or the star rotation period is shorter than 10 days.

355 **4 Radio emission from exoplanets with an Earth-like magnetosphere**

356 Radio emission from exoplanet magnetospheres and space weather conditions are closely
 357 connected. Radio emission measurements may provide information of the exoplanet magnetic
 358 field and, once the characteristics of the exoplanet magnetic field are inferred, insights about the
 359 space weather conditions generated by the host star on the exoplanet orbit. This section is ded-
 360 icated to the analysis of the influence of the space weather conditions, from regular to CME-like,
 361 on the radio emission generation, providing simplified new tools for the interpretation of radio
 362 telescopes observational data.

363 The interaction of the SW with a planetary magnetosphere can be analyzed using the anal-
 364 ogous of a flow facing a magnetized object, leading to the partial transfer of the flow energy. The
 365 transferred energy is transformed to radiation and the radiation power (P_{disp}) is proportional to
 366 the intercepted flux of the magnetic energy. Thus, following the radio-magnetic Bode's law, the
 367 incident magnetized flow power and the obstacle magnetic field intensity can be used to approx-
 368 imate the radio emission as $P_w = \beta [P_{disp}]^n$, with P_w the radio emission power, β the efficiency
 369 of dissipated power to radio emission conversion with $n \approx 1$ (Zarka et al., 2001; Zarka, 2007)
 370 and $\beta \approx 2 \cdot 10^{-3} - 10^{-2}$ (Zarka, 2018).

The power dissipated in the interaction between the SW with the magnetosphere is calcu-
 lated at the exoplanet day side. Irreversible processes in the interaction convert internal, bulk flow
 kinetic and magnetic energy into the kinetic energy required to accelerate the electrons along the
 magnetic field lines, and leading to cyclotron-maser radiation emission by these accelerated elec-
 trons. The energy transfer can be evaluated analyzing the energy fluxes of the system. There is
 a detailed discussion of the flux balance in Varela, J. et al. (2018). The radio emission is calcu-
 lated using the net magnetic power deposited on the exoplanet day side (Zarka et al., 2001; Zarka,
 2018, 2007):

$$P_w = 2 \cdot 10^{-3} P_B = 2 \cdot 10^{-3} \int_V \vec{\nabla} \cdot \frac{(\vec{v} \wedge \vec{B}) \wedge \vec{B}}{\mu_0} dV$$

371 with P_B the divergence of the magnetic Poynting flux associated with the hot spots of energy trans-
 372 fer in the exoplanet day side and V the volume enclosed between the bow shock nose and the mag-
 373 netopause.

374 In the following, the radio emission is calculated during regular and CME-like space weather
 375 conditions, modifying the SW dynamic pressure as well as IMF intensity and orientation of the
 376 model. First, the effect of the SW dynamic pressure and IMF intensity on the radio emission is
 377 analyzed separately. Next, the trends of the radio emission with respect to the SW dynamic pres-
 378 sure and IMF intensity are evaluated together.

379 **4.1 Effect of the SW dynamic pressure**

380 This section is dedicated to the study of the exoplanet radio emission generation with re-
 381 spect to the SW density and velocity, hence the SW dynamic pressure. Particular emphasis is ded-
 382 icated to clarify the link between bow shock compression and radio emission generation.

383 Figure 5 shows the logarithm of the radio emission power at the exoplanet day side for a
 384 set of SW dynamic pressure values increasing the SW velocity (fixed the SW density to 12 cm^{-3} ,

$P_d \leq 10$ (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

Table 5. Regression parameters in simulations with different SW velocity and density values. (a) Variable SW parameter in the data regression, (b) Γ factor and (c) α exponent. Trends in the simulations with $P_d \leq 10$ nPa and $P_d > 10$ nPa are analyzed separately.

385 panel a) and increasing the SW density (fixed the SW velocity to 350 km/s, panel b) for a star-
 386 exoplanet IMF orientation with $|B|_{IMF} = 10$ nT. Simulations with $P_d < 10$ nPa are analyzed
 387 separately due to the effect of the magnetosphere thermal pressure on the magnetopause stand-
 388 off distance, negligible in the simulations with $P_d \geq 10$ nPa (Varela, J. et al., 2022).

389 The radio emission increases from 10^6 to 10^{10} W as the SW increases from regular to super
 390 CME-like space weather conditions. The order of magnitude of the radio emission power calcu-
 391 lated in the simulations is consistent with Zarka (2018) scaling (around $6 \cdot 10^7$ W) for SW ve-
 392 locity values between 500 – 1200 km/s ($P_d = 2.5 - 14$ nPa) and SW density values between
 393 $30 - 120 \text{ cm}^{-3}$ ($P_d = 3.1 - 13.3$ nPa), that is to say, the radio emission values obtained from
 394 the simulations and the scaling are similar for regular space weather conditions. If $P_d < 2.5$ nPa,
 395 the radio emission power is below 10^7 W. For common CME-like conditions ($15 < P_d < 40$
 396 nPa) the radio emission power increases up to $6 \cdot 10^8$ W. During strong CME-like space weather
 397 conditions ($40 < P_d < 100$ nPa) the radio emission power reaches 10^9 W. For super CME-
 398 like space weather conditions ($P_d > 100$ nPa) the radio emission power is $2 \cdot 10^9$ W. The en-
 399 hancement of the radio emission as P_d increases is caused by a higher net magnetic power dis-
 400 sipation at the exoplanet day side as the magnetosphere compression intensifies.

401 Next, the trends of the radio emission with respect to the SW density and velocity are an-
 402 alyzed. Figure 6, panels a and c, show the fit of the radio emission power to the square value of
 403 the SW velocity $P_w \propto \Gamma(v_{sw}^2)^\alpha$ if $P_d \leq 10$ nPa and > 10 nPa, respectively. Figure 6, panels
 404 b and d, show the fit of the radio emission power to the SW density $P_w \propto \Gamma(n_{sw})^\alpha$ if $P_d \leq 10$
 405 nPa and > 10 nPa, respectively. The radio emission trends are analyzed separately in the simu-
 406 lations with $P_d \leq 10$ nPa and > 10 nPa to isolate the effect of the thermal pressure caused by
 407 the magnetosphere (for more information please see Varela, J. et al. (2022)). The parameters of
 408 the data regression are indicated in table 5.

The data fit finds similar exponents for the regression $P_w \propto (v_{sw}^2)^\alpha$ and $P_w \propto (n_{sw})^\alpha$ if
 $P_d \leq 10$ nPa, that is to say, proportional to the SW dynamic pressure. The scaling of the radio
 emission with respect to the SW dynamic pressure is stronger in simulations with $P_d > 10$ nPa,
 thus the radio emission generation is further promoted in a compressed magnetosphere. This is
 explained by the enhancement of the Poynting flux divergence as the magnetopause is located
 closer to the exoplanet surface. The regression parameters can be compared with the theoret-
 ical expression of the radio emission induced by a magnetized flow dominated by the dynamic
 pressure facing a magnetized obstacle (Zarka, 2018, 2007):

$$P_W = \beta \frac{|B_{IMF,\perp}|^2 B_{ex}^{2/3}}{\mu_0^{4/3}} \left(\frac{v_{sw}}{m_p n_{sw}} \right)^{1/3} R_{ex}^2 \pi \frac{2.835}{K^{1/3}}$$

409 with $B_{IMF,\perp}$ the perpendicular component of the IMF with respect to the flow velocity, B_{ex} the
 410 intensity of the magnetic field in the equator of the magnetized obstacle, μ_0 the vacuum magnetic

411 permeability and $K = 1-2$. Here, the intercepted flux of magnetic energy is estimated as $P_{disp} =$
 412 $\epsilon (v_{sw} |B_{IMF,\perp}|^2 / \mu_0) \pi R_{obs}^2$ with $\epsilon = M_A / (1 + M_A^2)^{1/2}$ (M_A Alfvénic Mach number), $R_{obs} = 1.5R_{mp}$
 413 and $R_{mp} = R_{ex} (2B_{ex} / (\mu_0 K n_{sw} v_{sw}^2))^{1/6}$. Thus, the theoretical dependency of the radio emission
 414 power with the SW velocity is $v_{sw}^{0.33}$ and with the SW density is $n_{sw}^{-0.33}$. The radio emission calculated
 415 in the simulations (all dominated by the SW dynamic pressure because $P_{IMF} = 0.09$
 416 nPa) shows a stronger dependency with the SW velocity compared to the theoretical model. Re-
 417 garding the SW density, the simulations show a direct proportionality with the radio emission,
 418 not an inverse proportionality as the theoretical expression predicts. This discrepancy can be ex-
 419 plained by the enhancement of the magnetosphere compression and bow shock distortion as the
 420 SW dynamic pressure increases, that is to say, the theoretical expression cannot reproduce the
 421 effect of the bow shock compression associated with a modification of the energy fluxes, net mag-
 422 netic power dissipated and divergence of the magnetic Poynting flux in the magnetosphere day
 423 side. Thus, the theoretical scaling law could underestimate the radio emission power generated
 424 in exoplanets for space weather conditions leading to a strongly compressed bow shock.

425 The effect of the SW dynamic pressure on the radio emission generation is highlighted in
 426 figure 7, comparing the divergence of the Poynting flux in the bow shock and magnetopause re-
 427 gion for simulations with $v_{sw} = 300$ km/s ($P_d = 0.9$ nPa) and $v_{sw} = 3000$ km/s ($P_d = 90$
 428 nPa). The Poynting flux divergence is more than one order of magnitude higher in the simula-
 429 tion with $P_d = 90$ nPa, explaining the radio emission enhancement as the SW dynamic pres-
 430 sure increases. It should be noted that the maxima of the Poynting flux divergence is located closer
 431 to the exoplanet surface as P_d increases because the magnetosphere standoff distance is smaller.
 432 In addition, the local maxima of the Poynting flux divergence is displaced towards the South of
 433 the magnetosphere in both simulations, determined by the IMF orientation and in particular by
 434 the location of the reconnection region. From the observational point of view, radio telescopes
 435 may measure a signal with a more localized radio emission maxima as the bow shock compres-
 436 sion enhances, although the radio emission maxima should be more diffused as the bow shock
 437 compression is weakened.

438 4.2 Effect of the IMF intensity and orientation

439 In this subsection we analyze the effect of the IMF intensity and orientation on the exoplanet
 440 radio emission generation. In particular, the role of the reconnection between the IMF and the
 441 exoplanet magnetic field is explored, as well as the bow shock formation or dispersion as the SW
 442 dynamic pressure or the IMF magnetic pressure dominate, respectively.

443 The IMF can induce large distortions in the exoplanet magnetic field, modifying locally
 444 the topology of the magnetosphere, particularly in the reconnection regions between the exoplanet
 445 magnetic field and the IMF. Figure 8 shows the logarithm of the radio emission fixed $P_d = 1.2$
 446 nPa for different IMF orientations (exoplanet-star, northward, southward and ecliptic) and IMF
 447 intensities between 10 and 250 nT.

448 The same order of magnitude is obtained for the radio emission power comparing simu-
 449 lation results and Zarka (2018) scaling if the IMF intensity is between 20 - 125 nT for an exoplanet-
 450 star IMF, 10 - 125 nT for a northward IMF, 10 - 50 nT for a southward IMF and 10 - 70 nT for
 451 an ecliptic IMF. Consequently, the radio emission calculated in the simulations and the values
 452 predicted by the scaling are similar from regular to strong CME-like space weather conditions
 453 regarding the IMF intensity. The simulations also predict a radio emission power above 10^8 W
 454 during Super CME. The IMF orientation leading to the largest radio emission is the southward
 455 IMF, followed by the ecliptic and exoplanet-star IMF. The lowest radio emission is observed for
 456 the northward IMF. The variation of the radio emission values regarding the IMF orientation is
 457 explained by the location and intensity of the reconnection regions. The southward IMF orien-
 458 tation induces the strongest reconnection, located in the equatorial region of the magnetosphere
 459 leading to the smallest magnetopause standoff distance and the largest radio emission. Likewise,
 460 the northward IMF orientation causes the lowest radio emission because the reconnection region
 461 is located nearby the exoplanet poles and the magnetopause standoff distance is larger regard-

462 ing the other IMF orientations. It should be noted that the location of the radio emission max-
 463 ima and the reconnection regions are concomitant in the simulation, thus the radio emission max-
 464 ima displaces with the reconnection region as the IMF intensity increases; towards the equato-
 465 rial region for a southward IMF, the poles for a northward IMF, to the South of the magnetosphere
 466 for a star-exoplanet IMF, to the North for a exoplanet-star and tilted to a higher longitude for a
 467 IMF oriented in the equatorial plane.

468 Figure 9 shows the Poynting flux divergence in the bow shock and magnetopause region
 469 for simulations with an exoplanet-star IMF with $|B|_{IMF} = 30$ nT (panel a) and 250 nT (panel
 470 b). The radio emission is more than one order of magnitude larger in the simulation with $|B|_{IMF} =$
 471 250 nT.

472 The effect of the IMF orientation on the radio emission is larger in simulations with $|B|_{IMF} \geq$
 473 70 nT. On the other hand, simulations with $|B|_{IMF} < 70$ nT show similar radio emission val-
 474 ues for all the IMF orientations. This is explained by the absence of the bow shock in the sim-
 475 ulations with $|B|_{IMF} \geq 70$ nT, because the Alfvénic Mach number $M_A = v_{sw}/v_A < 1$ (v_A is the
 476 Alfvén speed). Simulations with $|B|_{IMF} < 70$ nT ($M_A > 1$) lead to the formation of the bow
 477 shock, showing two regions with a local maxima of the Poynting flux divergence: 1) the recon-
 478 nection region between the IMF and the exoplanet magnetic field, 2) the nose of the bow shock
 479 where the IMF lines are compressed and bent. Figure 10 shows the radio emission from the bow
 480 shock nose, panel a, and the reconnection regions, panel b, for a simulation with southward IMF
 481 and $|B|_{IMF} = 30$ nT. The compression and bending of the IMF lines lead to a local maxima of
 482 the Poynting flux divergence in the nose of the bow shock. On the other hand, the Poynting flux
 483 divergence is larger and more localized in the magnetopause region where the IMF and the ex-
 484 oplanet magnetic field reconnects, closer to the exoplanet surface. Consequently, if the bow shock
 485 exists, the Poynting flux divergence in the bow shock depends on the SW dynamic pressure as
 486 well, thus the role of the IMF orientation in the radio emission generation is smaller. Radio tele-
 487 scopes may measure a signal with well defined radio emission maxima if the bow shock does not
 488 exist, although showing a fast variability of the maxima location as the IMF orientation changes.

Figure 11 and table 6 show the fit of the radio emission values calculated in the simulations
 using the regression $P_w \propto \Gamma |B|_{IMF}^\alpha$. It should be noted that the IMF pressure in the simulations
 with $|B| > 50$ nT is larger than the SW pressure ($P_{IMF} > 1.2$ nPa). In such configurations the
 theoretical expression of the radio emission is (Zarka, 2018, 2007):

$$P_w = \beta \frac{v_{sw} |B_{IMF,\perp}|^{4/3}}{\mu_0} R_{ex}^2 B_{ex}^{2/3} 3.6\pi$$

489 Here, $R_{mp} = R_{ex} (2B_{ex}/|B_{IMF,\perp}|)^{1/3}$. Thus, the theoretical dependency of the radio emission power
 490 with the SW velocity is linear with the v_{sw} and a super linear with the intensity of an IMF per-
 491 pendicular to the plasma flow. Consequently, the scaling for the simulations with dominant dy-
 492 namic pressure or dominant IMF pressure must be analyzed separately.

493 The regression exponents indicate the radio emission dependency with the IMF intensity
 494 is weaker in simulations with dominant SW pressure compared to simulations with dominant IMF
 495 pressure. This is the opposite tendency with respect to the radio-magnetic scaling law that pre-
 496 dicta a stronger $|B|_{IMF}$ trend if the SW pressure is dominant ($|B_{IMF,\perp}|^2$). This inconsistency can
 497 be explained by the effect of the bow shock compression in the simulations. On the other hand,
 498 the regression exponents obtained in simulations with dominant IMF pressure and Southward
 499 / Northward IMF orientations are similar to the radio-magnetic scaling law if the dynamic pres-
 500 sure is dominant ($\alpha \approx 2$). That is to say, radio-magnetic scaling law and simulation lead to sim-
 501 ilar trends if the bow shock does not exist and the IMF is perpendicular to the SW velocity. Con-
 502 sequently, deviations appear if the IMF is unaligned with the exoplanet magnetic field axis and
 503 the role of bow shock compression is added in the analysis, effects not included in the radio-magnetic
 504 scaling law. In summary, the theoretical scaling law could underestimate the radio emission power
 505 generated in exoplanets during space weather conditions leading to the bow shock dispersion.

$M_A > 1$		
IMF	Γ	α
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

Table 6. Regression parameters in simulations with different IMF orientations and intensities. IMF orientation (first column), Γ factor (second column) and α exponent (third column). The trends in simulations with $M_A > 1$ and $M_A < 1$ are analyzed separately.

4.3 Combined effect of the SW dynamic pressure, IMF intensity and IMF orientation

The analysis of the combined effect of SW dynamic pressure, IMF intensity and orientation provides an improved approach of the radio emission generation trends, particularly during extreme space weather conditions that melds a large compression of the bow shock and an intense magnetic reconnection.

Figure 12 shows the logarithm of the radio emission with respect to the SW dynamic pressure, IMF intensity and orientation for CME-like space weather conditions ($P_d = 1.5 - 100$ nPa and $|B|_{IMF} = 50 - 250$ nT). It should be noted that the increment of the SW dynamic pressure in the simulations is done by increasing the velocity of the SW, thus the SW density is fixed in the simulations. The radio emission ranges from $3 \cdot 10^8$ W for common CME (20 nPa and 50 nT) to above 10^{10} W for super CME-like space weather conditions (100 nPa and 250 nT). A large bow shock compression (large SW dynamic pressure) combined with a strong reconnection between IMF and exoplanet magnetic field (IMF intensity is high) lead to a further enhancement of the radio emission. The simulations with large SW dynamic pressure show similar radio emission values independently of the IMF intensity and orientation. On the other hand, the radio emission show larger changes between simulations with different IMF intensity and orientation if the SW dynamic pressure is low. Again, this result is consistent with previous analysis because simulations with low SW dynamic pressure and large IMF (particularly if $M_A < 1$) show a larger effect of the IMF intensity and orientation on the radio emission.

Figure 13 and table 7 indicate the data fit and the parameters of the regression $\log P_W \propto \log Z + M \log(|B|_{IMF}) + N \log(P_d)$, respectively. This expression is derived from $P_W \propto Z|B|_{IMF}^M P_d^N$. The data regression includes simulations with dominant SW and dominant IMF pressure because the main part of the space weather conditions analyzed have a dominant SW pressure, indicated by the black dashed line in figure 12 (SW dominant cases above the line).

The regression parameters with respect to the IMF intensity show similar trends compared to simulations with fixed SW dynamic pressure if the bow shock exist ($M \approx 1$ and $\alpha \approx 1$, see table 6 and 7). On the other hand, the scaling with respect to the SW dynamic pressure is weaker compared to simulations with fixed IMF intensity and orientation ($N \approx 1$ although $\alpha \approx 1.8$ if $P_d > 10$ nPa, see table 5 and 7). Consequently, the simulations analysis indicate the effect of the IMF intensity on the radio emission is similar to the SW dynamic pressure if the bow shock exist and it is strongly compressed. In addition, there is a variation of the radio emission scaling with respect to the IMF orientation up to 20%, pointing out the important role of the IMF ori-

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

Table 7. Regression parameters in simulations with different SW dynamic pressure, IMF orientation and intensity. IMF orientation (first column), Z parameter (second column), M parameter (third column) and N parameter (fourth column).

539 entation on the radio emission generation. If the exponents of the data regression are compared
540 to the radio-magnetic scaling law for a dominant SW dynamic pressure, there is clear deviation
541 showing a weaker trend for $|B|_{IMF}$ ($M \approx 1$ versus 2) although stronger for P_d ($N \approx 1$ versus
542 0.17). Such difference is smaller if the regression exponents are compared to the radio-magnetic
543 scaling law for a dominant IMF pressure, showing a similar $|B|_{IMF}$ exponent ($M \approx 1$ versus 1.33)
544 and a P_d exponent 2 times larger ($N \approx 1$ versus 0.5). Indeed, the best agreement is obtained if
545 the IMF orientation is Southward ($M = 1.22$ and $N = 0.95$). Consequently, as it was previ-
546 ously discussed, the discrepancy with the radio-magnetic scaling law for the configurations with
547 dominant SW pressure could be caused by the effect of the bow shock compression.

548 **4.4 Analysis result consequences on the interpretation of radio telescope measure-** 549 **ments**

550 The analysis of the radio emission generated in exoplanet magnetospheres for different space
551 weather conditions provides useful information regarding the variability of the radio emission
552 signal measured by radio telescopes. In addition, an order of magnitude approximation of the ra-
553 dio emission generated by exoplanets with an Earth-like magnetosphere is provided for differ-
554 ent space weather conditions.

555 The combined effect of a strongly compressed bow shock and an intense reconnection be-
556 tween the IMF and the exoplanet magnetic field can lead to a large increase of the radio emis-
557 sion generation. For the case of an exoplanet with an Earth-like magnetic field, the radio emis-
558 sion can increase more than four orders of magnitude comparing regular and extreme space weather
559 conditions (super CME-like events for the case of the Earth).

560 The simulations indicate that the largest radio emission variability should be observed from
561 exoplanets hosted by stars with large magnetic activity and low SW dynamic pressure, leading
562 to space weather conditions that avoid the formation of the bow shock. The radio emission vari-
563 ation for a given SW dynamic pressure could be close to one order of magnitude regarding the
564 IMF orientation. On the other hand, if the exoplanet is hosted by stars with low magnetic activ-
565 ity although large SW dynamic pressure, the variability of the radio emission with the IMF ori-
566 entation should be small and mainly induced by changes on the SW dynamic pressure. The vari-
567 ation of the radio emission with the IMF in simulations with bow shock is smaller than a factor
568 1.5.

569 The study also shows that, if the host star generates a SW with large dynamic pressure and
570 an intense IMF, the effect of the IMF orientation should also induce a substantial variability on
571 the radio emission signal even if the bow shock exist, close to a factor 2. Consequently, a large
572 radio emission variability is linked to unfavorable space weather conditions because the host star
573 magnetic activity is large, leading to a strong reconnection between IMF and exoplanet magnetic
574 field, reducing the magnetopause standoff distance. The same way, a strong radio emission sig-
575 nal combined with a small variability indicates a compressed magnetosphere, that is to say, the

576 SW dynamic pressure generated by the host star is large also reducing the magnetosphere stand-
577 off distance.

578 The simulations scaling shows an underestimation of the exoplanet radio emission by the
579 theoretical scaling for space weather conditions leading to a strongly compressed or vanishing
580 bow shock. Consequently, the radio telescope sensibility required to measure the radio emission
581 generated by terrestrial planets inside the habitable zone of M, K, G and F stars could be lower
582 than expected.

583 The less restrictive conditions to the exoplanet habitability are linked to a radio emission
584 signal with rather low variability. This is the case for simulations with low SW dynamic pres-
585 sure and IMF intensity, that is to say, space weather conditions leading to magnetopause stand-
586 off distances further away from the exoplanet surface.

587 The inference of the the magnetic field intensity and topology of exoplanets may need long
588 periods of observational data if one wishes to isolate the effect of the space weather conditions
589 on the radio emission signal. The data filtering could be particularly challenging for the case of
590 exoplanets exposed to recurrent extreme space weather conditions or a dominant IMF pressure,
591 leading to a large radio emission variability. On the other hand, the identification of the magnetic
592 field characteristics for exoplanets facing more benign space weather conditions could be less
593 complex, because the variability of the radio emission data should be smaller.

594 Once the properties of the exoplanet magnetic field are identified, the analysis of the ra-
595 dio emission time series opens the possibility of tracking the space weather conditions on the ex-
596 oplanet orbit, providing important information about the host star as the magnetic field or SW
597 dynamic pressure.

598 **5 Conclusions and discussion**

599 Present study is dedicated to analyze the interaction between the stellar wind and exoplan-
600 ets with an Earth-like magnetosphere hosted by M stars and F star type τ Boo, in particular the
601 habitability restrictions induced by the sterilizing effect of the stellar wind on the exoplanet sur-
602 face if the magnetosphere shielding is inefficient. The radio emission generated by exoplanets
603 with an Earth-like magnetosphere is also calculated for different space weather conditions. With
604 that aim, a set of MHD simulations were performed reproducing the interaction of the stellar wind
605 with the exoplanet magnetosphere during regular and extreme space weather conditions.

606 The simulations results indicate that exoplanets with an Earth-like magnetosphere hosted
607 by a M star at 0.2 au are protected from the stellar wind during regular and CME-like space weather
608 conditions. This protection holds if the rotation period of the star is 3 days or larger, although fast
609 rotators can constrain the exoplanet habitability due to the generation of intense and recurrent
610 CME-like events (Aarnio, A. N. et al., 2012). Likewise, if the exoplanet orbit is at 0.1 au, the mag-
611 netosphere protection only holds for M stars with a rotation period of 12 days or larger. On the
612 other hand, if the exoplanet orbit is below 0.1 au, the magnetic field must be stronger regarding
613 the Earth to avoid the direct impact of the stellar wind at low latitudes, particular during CME-
614 like space weather conditions. It should be noted that the discussion about the properties of the
615 terrestrial exoplanet magnetic fields, for example the type of internal magnetic dynamo at differ-
616 ent orbits, the spinning rotation speed or the synchronicity with the host star are not explored in
617 this study, although these effects must be consider to improve the accuracy of the predictions (Stevenson,
618 D. J., 2003).

619 If the exoplanet is hosted by a F stars like τ Boo inside the habitable zone, regular space
620 weather conditions do not impose strong constraint on the habitability. On the other hand, if the
621 exoplanet orbit is close to the inner boundary of the habitable zone (2.5 au), an efficient shield-
622 ing during CME-like space weather conditions requires a stronger magnetic field compared to
623 the Earth. The introduction of the effect of the star rotation in the analysis indicates that the di-
624 rect precipitation of the SW can occur if the star rotation period is below 10 days for exoplan-

625 ets at 2.5 au during extreme space weather conditions, although for exoplanets at 5 au the star
626 rotation period must be 2 days or lower.

627 The radio emission calculated in simulations with a dynamic pressure between $P_d = 2.5\text{--}$
628 14 nPa shows the same order of magnitude regarding the scaling proposed by Zarka (2018), pre-
629 dicting $7.5 \cdot 10^7\text{ W}$. That is to say, the radio emission obtained in the simulations is consistent
630 with the scaling during regular and weak CME-like space weather conditions. Likewise, simu-
631 lations with fixed dynamic pressure ($P_d = 1.2\text{ nPa}$) also show radio emission values compa-
632 rable with Zarka (2018) scaling if the IMF intensity is in the range of values observed during reg-
633 ular to strong CME-like space weather conditions. In addition, the southward IMF orientation
634 leads to the strongest radio emission and the northward IMF to the lowest. The simulations indi-
635 cate an enhancement of the radio emission as the stellar wind dynamic pressure and IMF in-
636 tensity increase. Consequently, radio telescopes may receive a stronger signal from exoplanets
637 hosted by stars with large magnetic activity and intense stellar wind (high SW density and ve-
638 locity), particularly if the exoplanet orbit is close to the star. Nevertheless, such adverse space
639 weather conditions requires an exoplanet with a intense magnetic field that avoids the collapse
640 of the magnetopause on the exoplanet surface. Such ensemble of space weather and exoplanet
641 magnetic field characteristics are found in Hot Jupiters, reason why the first potential detection
642 of radio emission from an exoplanet involved the Hot Jupiter $\tau\text{ Boo b}$ (Turner, J. D. et al., 2021).
643 Unfortunately, the radio emission detection from exoplanets hosted by stars with more favorable
644 habitability conditions regarding the space weather inside habitable zone, will require a new gen-
645 eration of radio telescopes with improved resolution and sensibility because the radio emission
646 signal should be several orders of magnitude smaller compared to Hot Jupiters.

647 The simulations indicate a larger variability of the exoplanet radio emission induced by the
648 IMF orientation if the bow shock does not exist, that is to say, the stellar wind dynamic pressure
649 is low enough and the IMF intensity high enough to be in the parametric range of $M_A < 1$. On
650 the other hand, the radio emission variability caused by the IMF orientation is smaller if the bow
651 shock exist ($M_A > 1$). That happens because, if the bow shock exist, there is a component of
652 the radio emission linked to the compression and bending of the IMF lines in the nose of the bow
653 shock, mainly dependent on the dynamic pressure of the stellar wind. Thus, the radio emission
654 sources are the bow shock compression and the reconnection site between IMF and exoplanet
655 magnetic field. Consequently, the role of the IMF orientation is smaller with respect to the con-
656 figurations without bow shock. The implication of this result is that exoplanet magnetospheres
657 routinely perturbed by intense IMF avoiding the formation of the bow shock ($M_A < 1$) may show
658 a larger radio emission variability with respect to exoplanet magnetospheres with a bow shock.
659 That is to say, if the exoplanet is hosted by a star with strong magnetic activity although relative
660 low stellar wind dynamic pressure, the radio telescopes may measure a large time variability in-
661 duced by changes in the IMF orientation, particularly if the magnetosphere erosion leads to a mag-
662 netopause located close to the exoplanet surface. Hence, if radio telescopes routinely measure
663 relatively strong and very variable signal, the exoplanet habitability conditions may not be op-
664 timal from the point of view of the space weather and the exoplanet magnetic field intensity. The
665 same way, if the host star has a relative weak magnetic activity although generates intense stel-
666 lar winds (large dynamic pressure), the radio emission detected must be relatively large and show
667 a small variability, pointing out a large compression of the exoplanet magnetosphere and low mag-
668 netopause standoff distances, thus the exoplanet habitability state regarding the space weather
669 conditions and the intrinsic magnetic field is less favorable. Therefore, the combination of low
670 radio emission and small variability may indicate the space weather conditions and the intrin-
671 sic magnetic field of the exoplanet support lower limitations for the exoplanet habitability, ef-
672 ficiently shield by the magnetosphere from the sterilizing effect of the stellar wind.

673 The analysis of the simulations combining the effect of the SW dynamic pressure with the
674 IMF orientation and intensity shows radio emission values between $3 \cdot 10^7\text{ W}$ for common CME
675 up to $2 \cdot 10^{10}\text{ W}$ for super CME. The simulations with large SW dynamic pressure and IMF in-
676 tensity leads to an enhancement of the radio emission because the bow shock is strongly com-
677 pressed, the reconnection between the IMF and the exoplanet magnetic field is strong and the mag-

678 netopause is located close to the exoplanet surface. The statistical analysis shows similar radio
 679 emission trends with respect to the SW dynamic pressure and IMF intensity, although the scal-
 680 ing is slightly affected by the IMF orientation. In particular, the southward IMF leads to the largest
 681 IMF intensity dependency, 20% larger with respect to the SW dynamic pressure trend.

Statistical analysis of the radio emission calculated in the simulations leads to data regres-
 sion exponents that deviate with respect to the radio-magnetic scaling laws (Zarka, 2018, 2007).
 Nevertheless, the agreement improves comparing the radio-magnetic scaling law of a configura-
 tion with dominant IMF pressure and the data regression for a Southward IMF orientation. Con-
 sequently, the trends of radio-magnetic scaling law and simulations are similar if the bow shock
 does not exist and the IMF is perpendicular to the SW velocity. That means the radio-magnetic
 scaling laws does not fully capture the effect of the bow shock compression and magnetosphere
 distortion on the radio emission generation due to the combined effect of the SW and IMF. The
 scaling law obtained from the simulation is, including the range of exponent values calculated
 for different IMF orientations:

$$P_w \propto |B_{IMF}^{(0.9-1.22)} P_d^{(0.95-1.15)}$$

682 that is to say, the radio-magnetic scaling law for space weather conditions with a dominant SW
 683 pressure could overestimate the trend of the IMF intensity ($P_w \propto |B_{IMF,\perp}|^2$) and underestimate
 684 the trend of the SW dynamic pressure ($P_w \propto P_d^{0.17}$). On the other hand, the prediction of the
 685 radio-magnetic scaling law for space weather conditions with a dominant IMF pressure is closer
 686 to the simulations scaling regarding the IMF intensity ($P_w \propto |B_{IMF,\perp}|^{1.3}$) and the SW dynamic
 687 pressure $P_w \propto P_d^{0.5}$). In summary, the theoretical scaling may underestimate the radio emission
 688 generation, particularly with respect to the SW dynamic pressure trend.

689 A further refinement of the simulations scaling requires an improved description of the model's
 690 physics, for example introducing the exoplanet rotation and kinetic effects. Nevertheless, the present
 691 study provides a first order approximation of the exoplanet standoff distance and magnetospheric
 692 radio emission with respect to the space weather conditions generated by host star.

693 Appendix A Numerical model validation

694 The numerical model used in this study was also applied in the analysis of the interaction
 695 between the solar wind and the Earth magnetosphere (Varela, J. et al., 2022). Part of Varela, J.
 696 et al. (2022) study was dedicated to analyze the perturbation induced in the magnetosphere by
 697 several CMEs that impacted the Earth from 1997 to 2020. The simulations results were compared
 698 with observational data to validate the numerical model, in particular the K_p index. The K_p in-
 699 dex provides the global geomagnetic activity taking values from 0 if the geomagnetic activity is
 700 weak to 9 if the geomagnetic activity is extreme (Menvielle, M. & Berthelier, A., 1991; Thom-
 701 sen, M. F., 2004). The K_p index was calculated in the simulations as the lowest latitude with open
 702 magnetic field lines in the Earth surface at the North Hemisphere. Figure A1 shows the corre-
 703 lation between the K_p index obtained in the simulations with respect to the measured values. The
 704 statistical analysis finds a correlation coefficient of 0.83, that is to say, a reasonable agreement
 705 between simulations and observational data. Consequently, the numerical model is valid to re-
 706 produce the global structures of the Earth magnetosphere during extreme space weather condi-
 707 tions, also suitable to analyze the interaction of the stellar wind with exoplanet magnetospheres
 708 if the intrinsic magnetic field is similar to the Earth.

709 Appendix B Calculation of the magnetopause standoff distance

The theoretical approximation of the magnetopause standoff distance is calculated as the
 balance between the dynamic pressure of the SW ($P_d = m_p n_{sw} v_{sw}^2 / 2$), the thermal pressure of
 the SW ($P_{th,sw} = m_p n_{sw} v_{th,sw}^2 / 2 = m_p n_{sw} c_{sw}^2 / \gamma$), and the magnetic pressure of the IMF ($P_{mag,sw} =$
 $B_{sw}^2 / (2\mu_0)$) with respect to the magnetic pressure of a dipolar magnetic field ($P_{mag,ex} = \alpha \mu_0 M_{ex}^2 / (8\pi^2 r^6)$)
 and the thermal pressure of the magnetosphere ($P_{th,MSP} = m_p n_{MSP} v_{th,MSP}^2 / 2$). This results in

the expression:

$$P_d + P_{mag,sw} + P_{th,sw} = P_{mag,ex} + P_{th,MSP} \quad (B1)$$

$$\frac{R_{mp}}{R_{ex}} = \left[\frac{\alpha \mu_0 M_{ex}^2}{4\pi^2 \left(m_p n_{sw} v_{sw}^2 + \frac{B_{sw}^2}{\mu_0} + \frac{2m_p n_{sw} c_{sw}^2}{\gamma} - m_p n_{BS} v_{th,MSP}^2 \right)} \right]^{(1/6)} \quad (B2)$$

with M_{ex} the exoplanet dipole magnetic field moment, $r = R_{mp}/R_{ex}$, and α the dipole compression coefficient ($\alpha \approx 2$ (Gombosi, 1994)). This approximation does not include the effect of the reconnections between the IMF with the exoplanet magnetic fields, thus the expression assumes a compressed dipolar magnetic field, ignoring the orientation of the IMF. Here, the approximation is only valid if the IMF intensity is rather low and the magnetopause standoff distance should be calculated using simulations for extreme space weather conditions.

The magnetopause standoff distance is defined in the simulations analysis as the last close magnetic field line on the exoplanet dayside at 0° longitude in the ecliptic plane.

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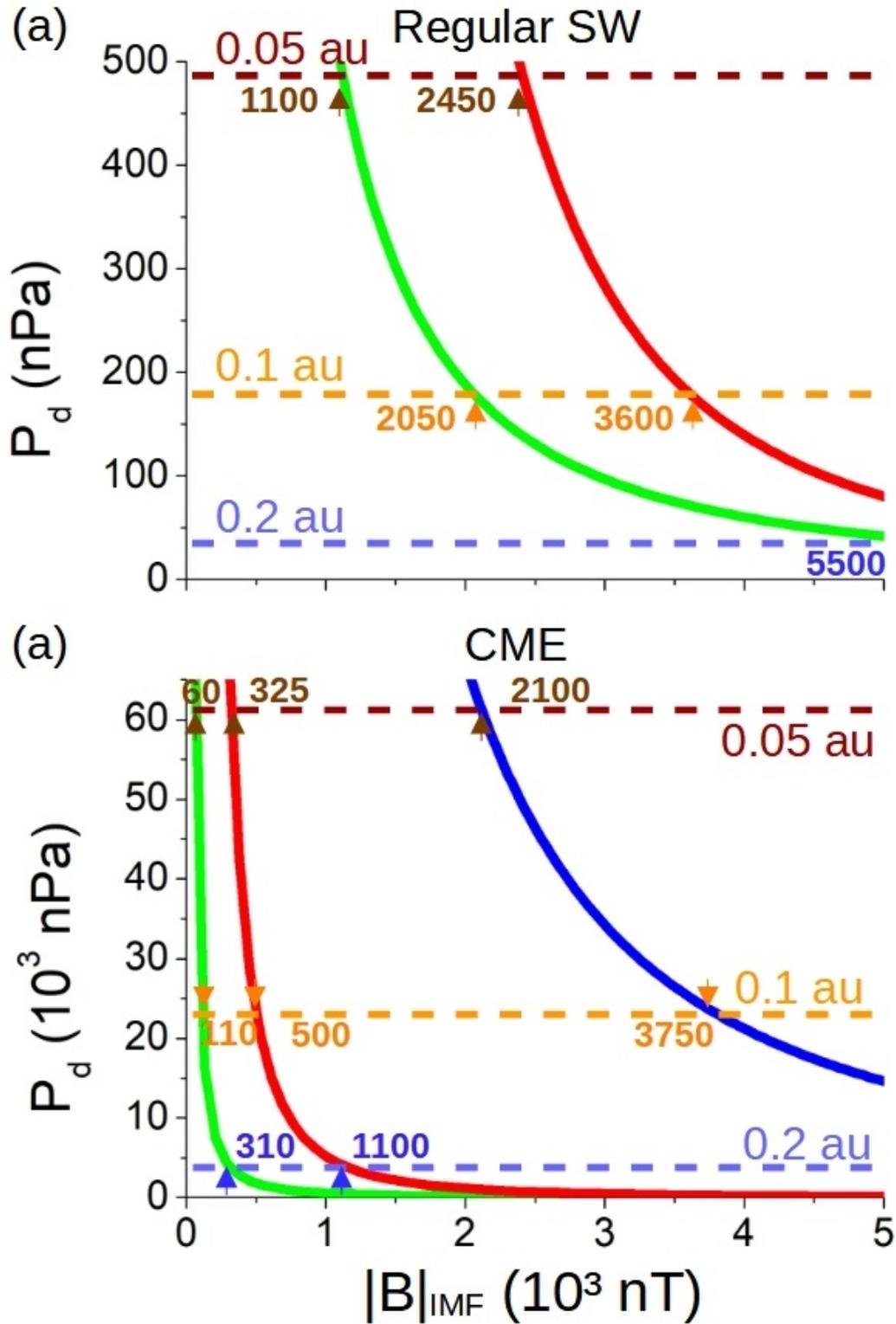
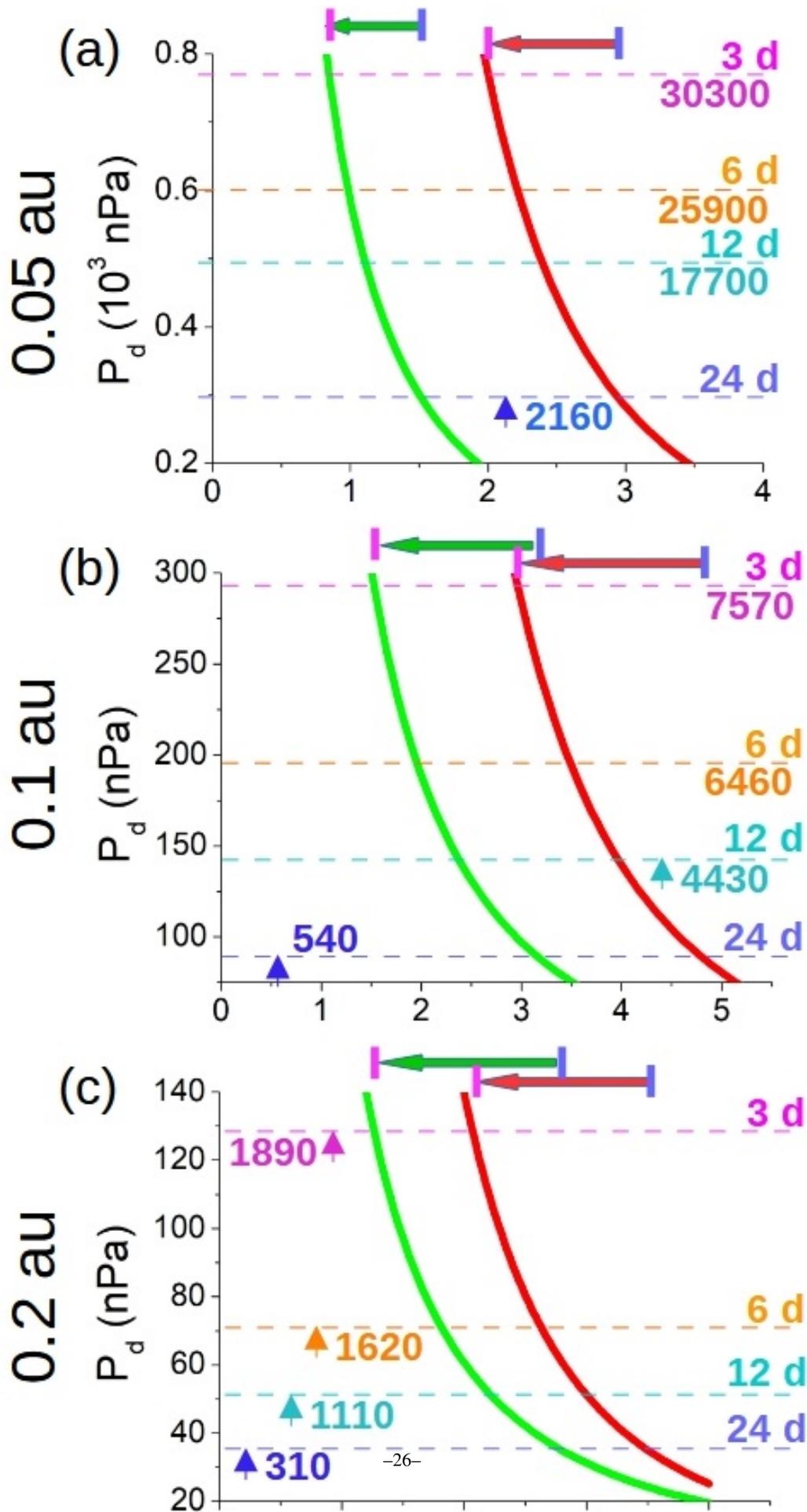


Figure 1. Critical IMF intensity and SW dynamic pressure required for the direct precipitation of the SW towards the exoplanet surface for (a) regular and (b) CME-like space weather conditions. IMF orientation: Exoplanet-star (red line), southward (green line) and northward (blue line). The horizontal dashed lines indicate the SW dynamic pressure at different exoplanet orbits: 0.05 au (red), 0.1 au (orange) and 0.2 au (blue). The critical IMF intensity is indicated for each IMF orientation.



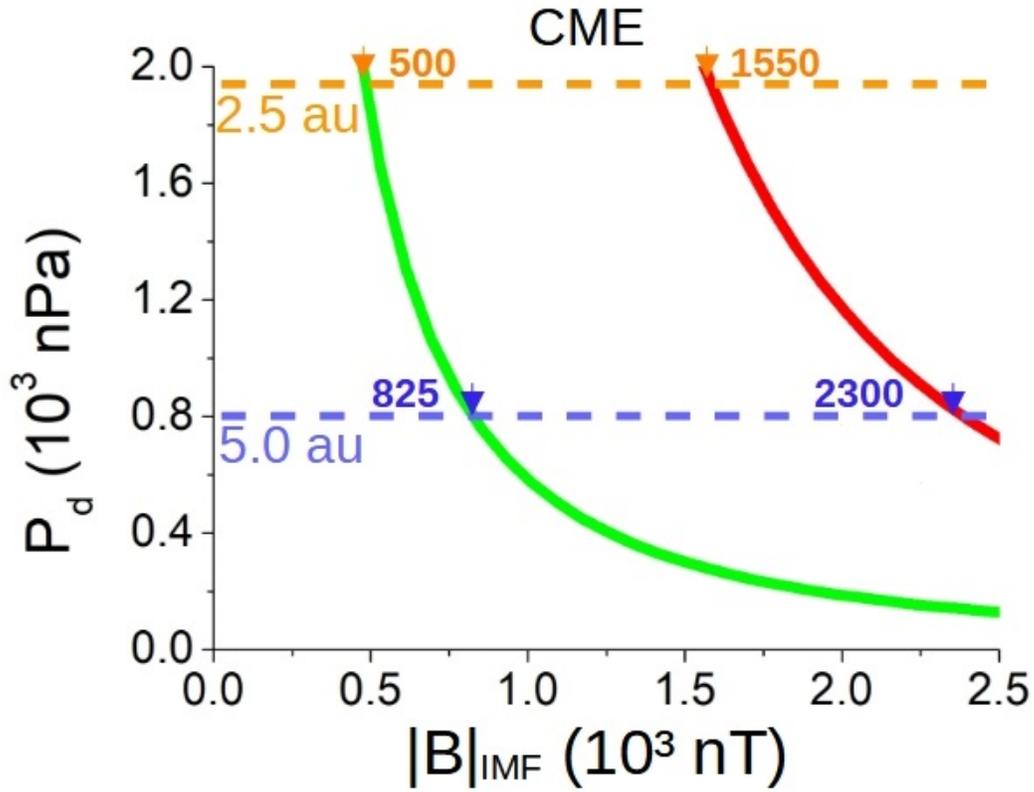


Figure 3. Critical IMF intensity and SW dynamic pressure required for the direct precipitation of the SW towards the exoplanet surface during CME-like space weather conditions. IMF orientation: Exoplanet-star (red line) and southward (green line). The horizontal dashed lines indicate the SW dynamic pressure at different exoplanet orbits: 2.5 au (orange) and 5.0 au (blue). The critical IMF intensity is indicated for each IMF orientation.

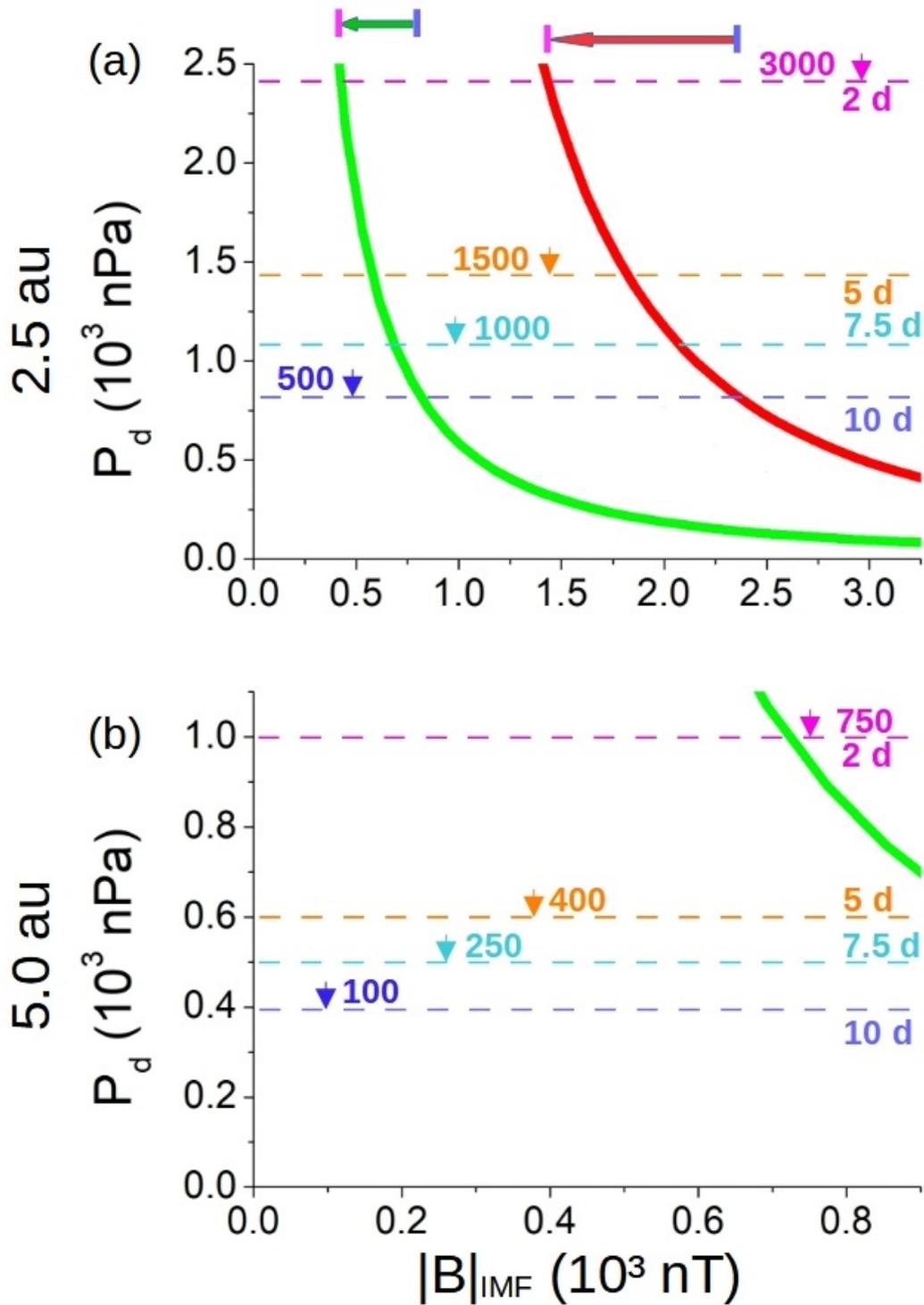


Figure 4. Critical IMF intensity and dynamic pressure required for the direct precipitation of the SW considering different F star rotation periods and exoplanets located at 2.5 au (a) and 5.0 au (b) orbits. IMF orientation: Exoplanet-star (red line) and southward (green line). The horizontal dashed lines indicate the SW dynamic pressure for F stars with rotation periods: 10 days (blue), 7.5 days (light cyan), 5 days (orange) and 2 days (pink). The bold colored arrows show the decrease of the critical IMF intensity required for the direct SW deposition if the F star rotation increases from 10 to 2 days. The green (red) color of the bold arrow indicates a southward (exoplanet-star) IMF orientation. The tentative critical IMF intensity is indicated for each star rotation rate.

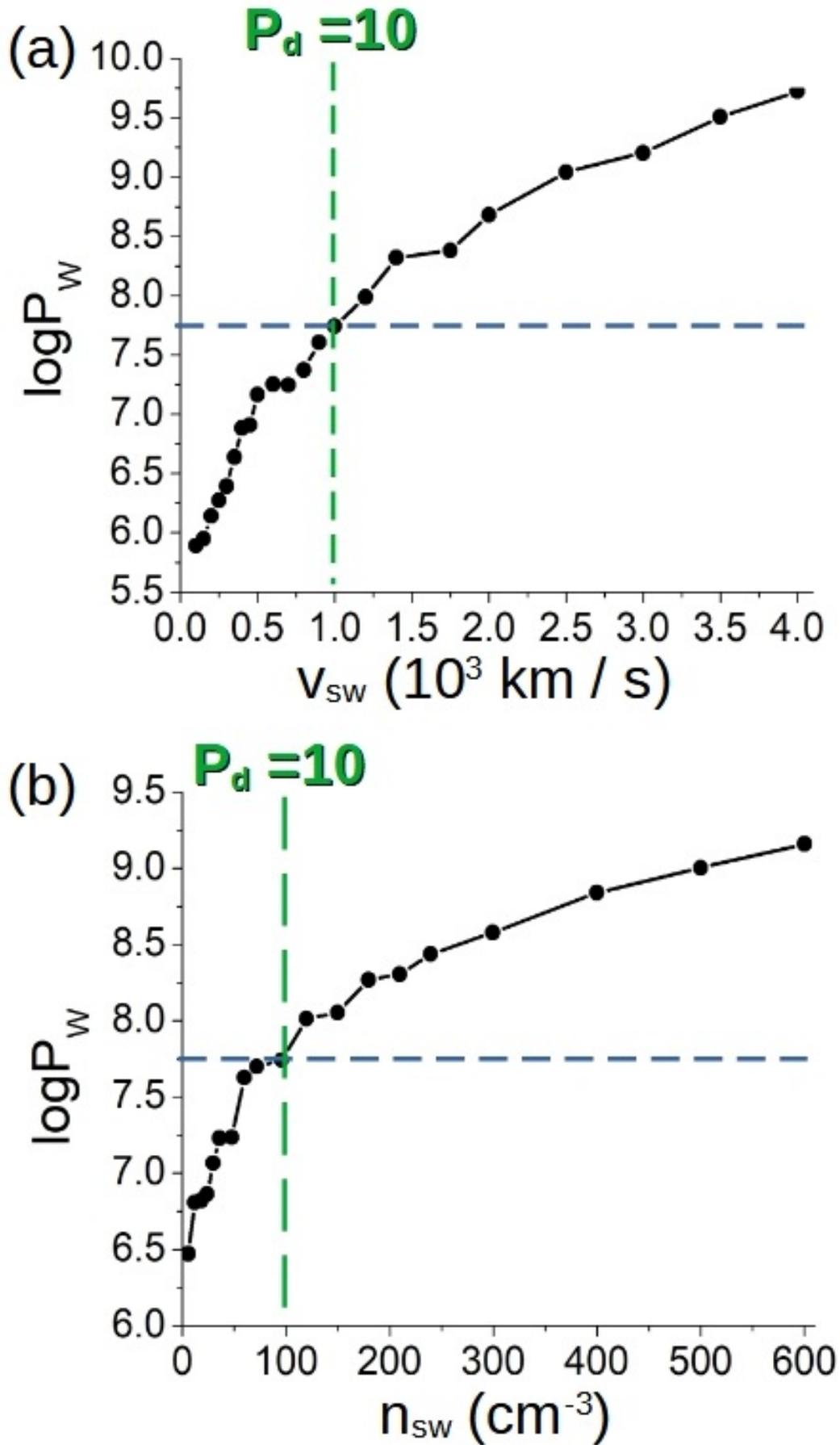


Figure 5. Radio emission power generated in the day²⁹ side of the exoplanet magnetosphere for a star-exoplanet IMF orientation with $|B_{IMF}| = 10$ nT if (a) the SW density is fixed to 12 cm^{-3} and the SW velocity

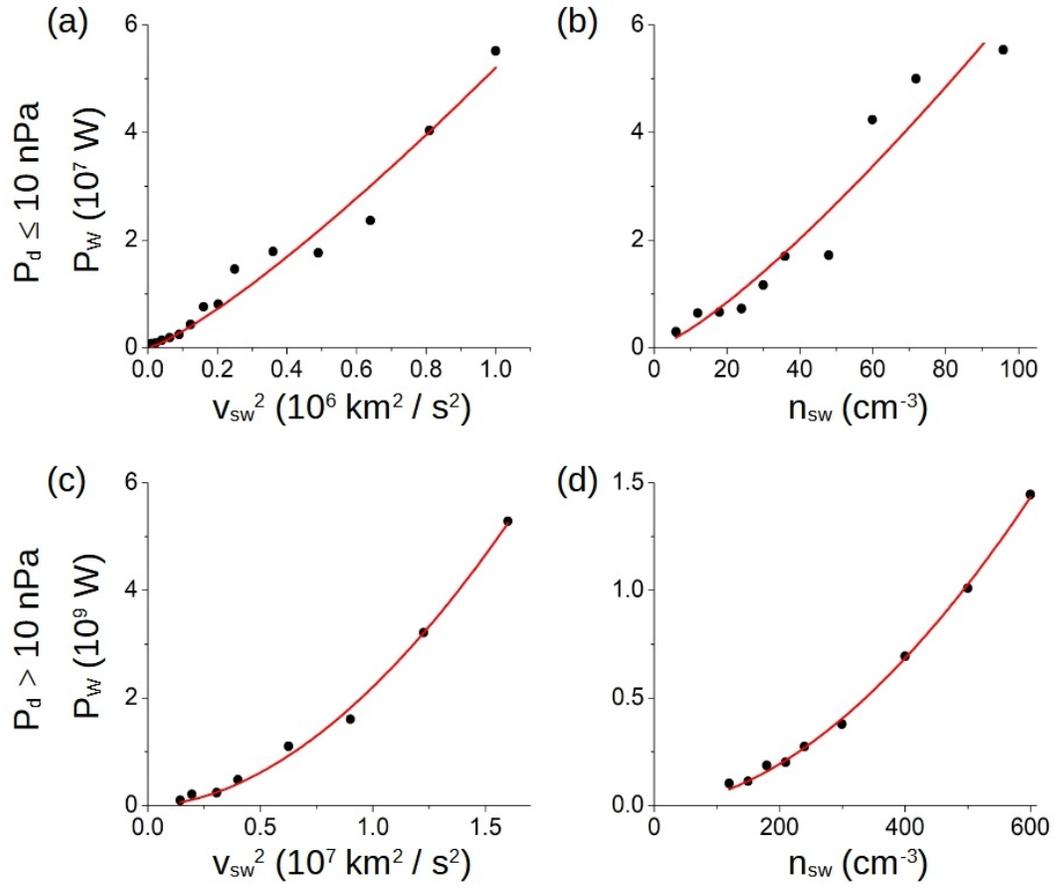


Figure 6. Data regression of the radio emission with respect to the square value of the SW velocity for (a) $P_d \leq 10$ and (c) $P_d > 10$. Data regression of the radio emission with respect to the SW density for (b) $P_d \leq 10$ and (d) $P_d > 10$.

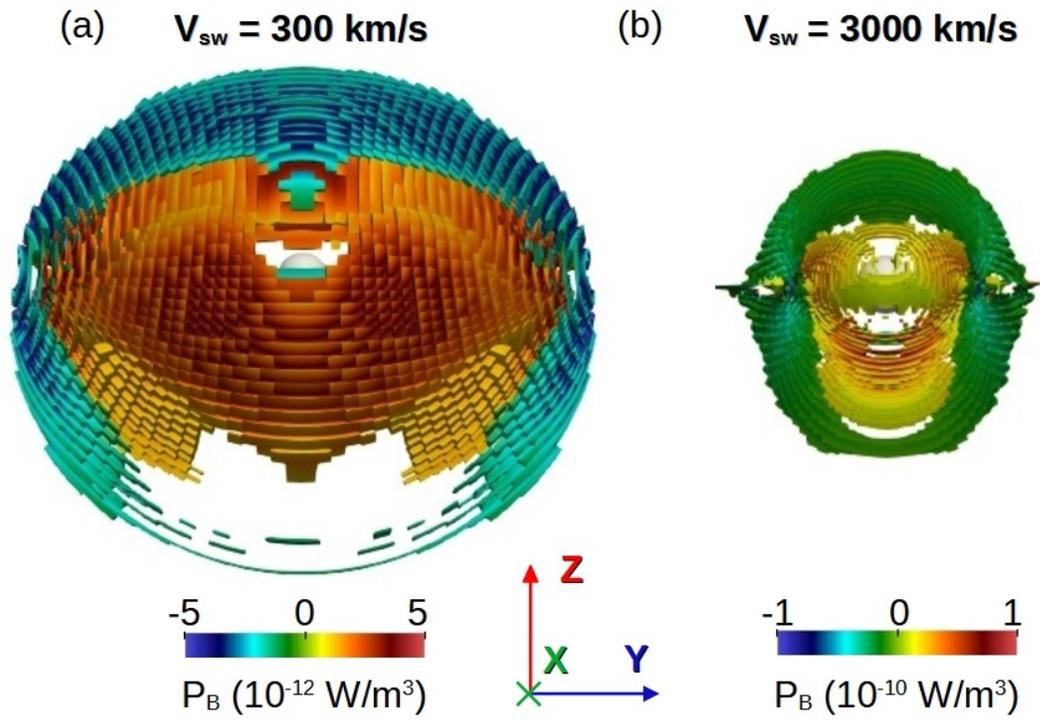


Figure 7. Iso-volume of the Poynting flux divergence in the bow shock and magnetopause region for simulations with (a) $v_{sw} = 300 \text{ km/s}$ and (b) $v_{sw} = 3000 \text{ km/s}$. Star-exoplanet IMF orientation with $|B|_{IMF} = 10 \text{ nT}$ and SW density of 12 cm^{-3} . Both panels show plots with the same dimensional scale.

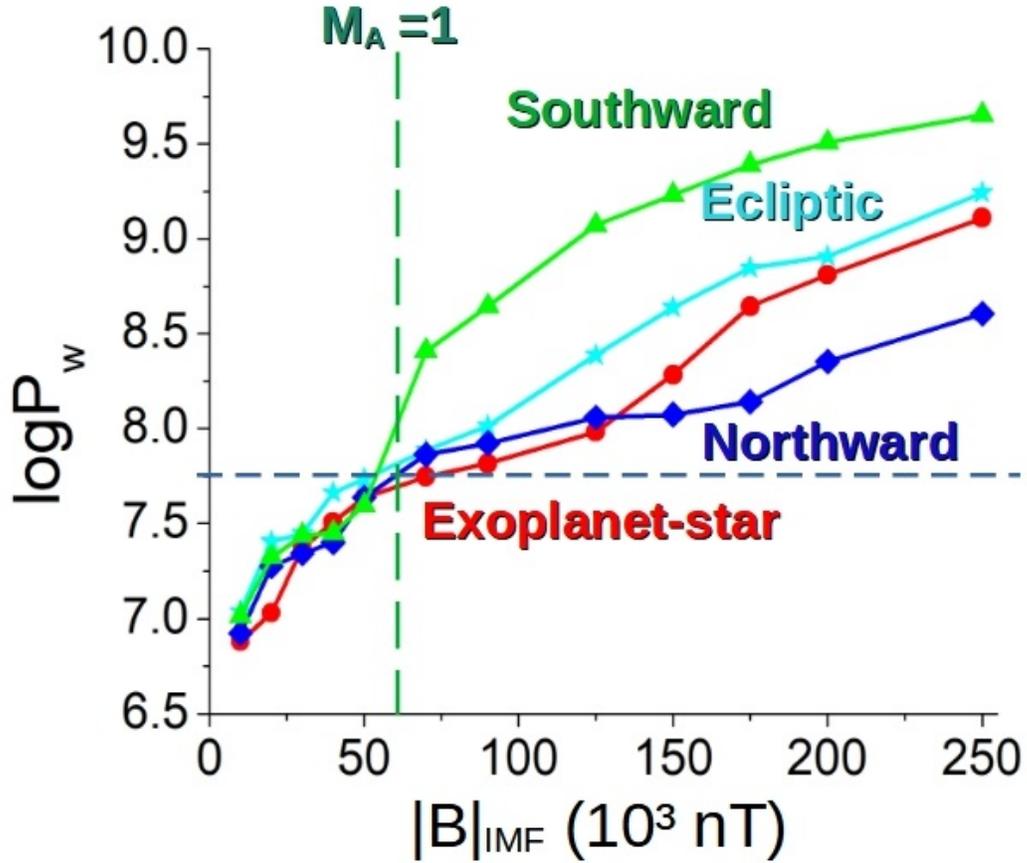


Figure 8. Logarithm of the radio emission power for simulations with $P_d = 1.2$ nPa and $|B|_{IMF} = 10 - 250$ nT. IMF orientations: Exoplanet-star (red dots), northward (blue diamonds), southward (green triangle) and ecliptic (cyan stars). The blue dashed horizontal line indicate the radio emission range derived from the scaling law by (Zarka, 2018). The dark green dashed vertical line indicates the simulations with $M_A < 1$ (right) and $M_A > 1$ (left).

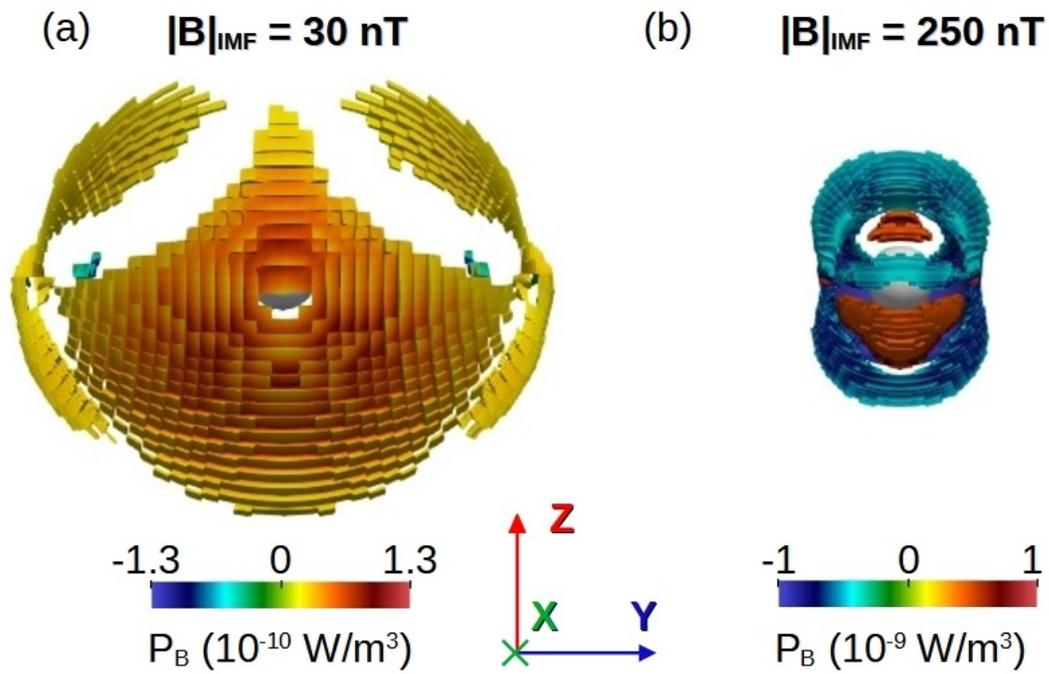


Figure 9. Iso-volume of the Poynting flux divergence in the bow shock and magnetopause region for simulations with (a) $|B|_{IMF} = 30 \text{ nT}$ and (b) $|B|_{IMF} = 250 \text{ nT}$. Exoplanet-star IMF orientation and $P_d = 1.2 \text{ nPa}$. Both panels show plots with the same dimensional scale.

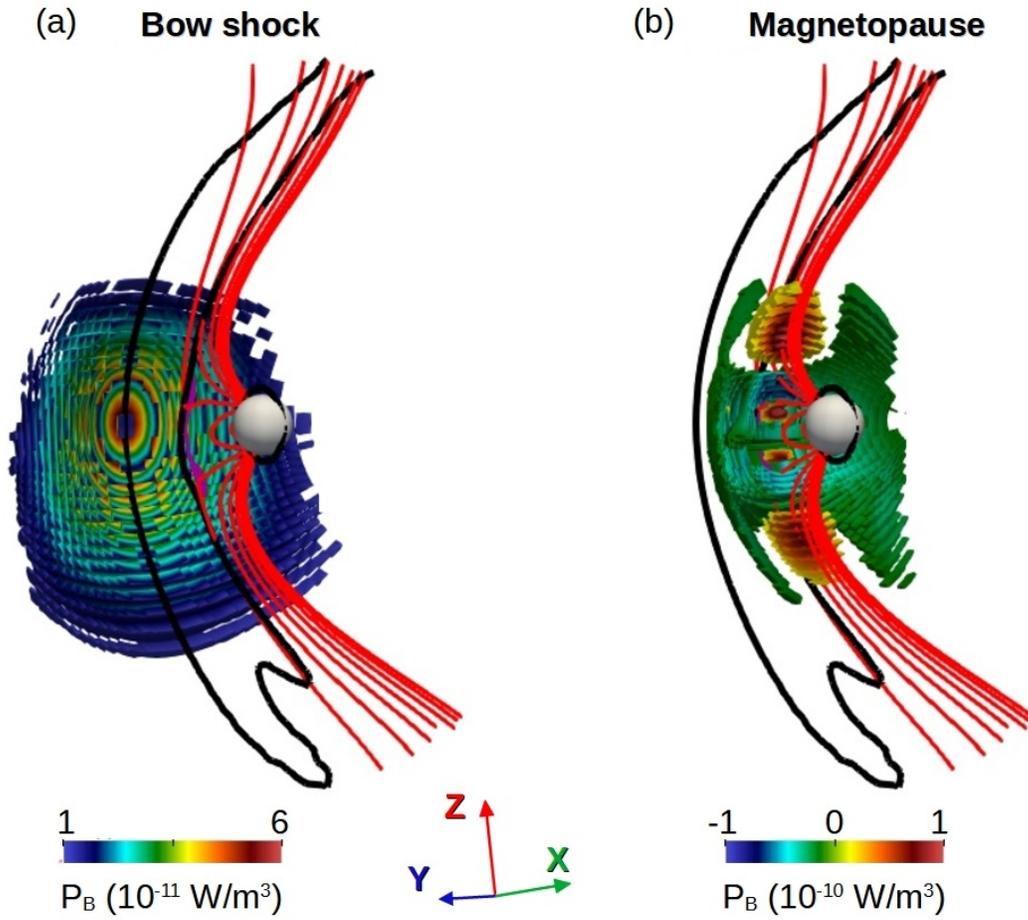


Figure 10. Poynting flux divergence in (a) the bow shock nose and (b) magnetopause reconnection regions. Simulation with southward IMF orientation, $|B|_{IMF} = 30$ nT and $P_d = 1.2$ nPa. Black lines indicate the region of the bow shock ($n > 20$ cm⁻³), the red lines the exoplanet magnetic field lines and the pink iso-surface the reconnection region in the XZ plane ($|B| < 5$ nT).

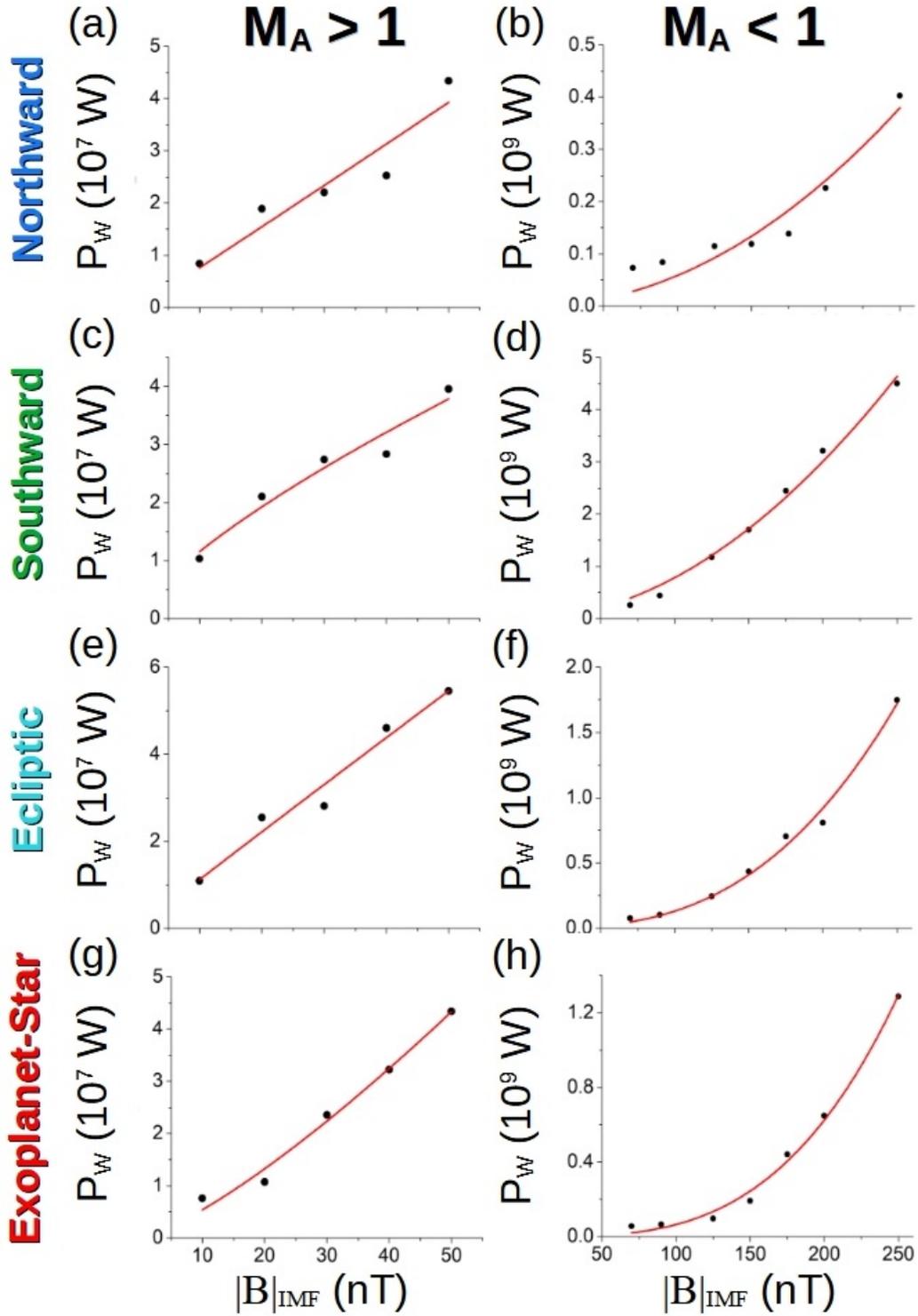


Figure 11. Data fit of the regression $P_w \approx \Gamma |B|_{sw}^\alpha$ if $|B|_{sw} < 70$ for (a) northward, (c) southward, (e) ecliptic and (g) exoplanet-star IMF. Same data regression if $|B|_{sw} \geq 70$ for (b) northward, (d) southward, (f) ecliptic and (h) exoplanet-star IMF.

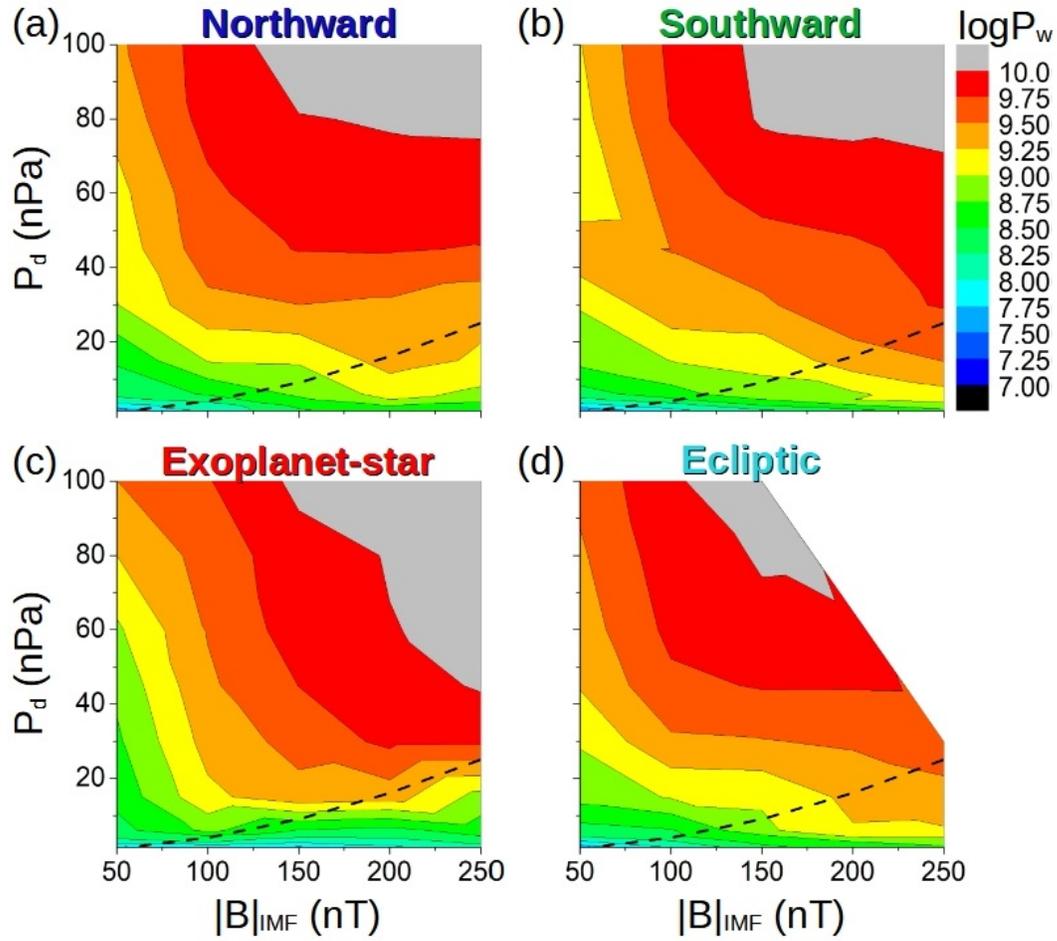


Figure 12. Logarithm of the radio emission with respect to the SW dynamic pressure and IMF intensity for (a) northward, (b) southward, (c) exoplanet-star and (d) ecliptic orientation. The dashed black line indicates the simulations with dominant SW pressure (above the line) and dominant IMF pressure (below the line).

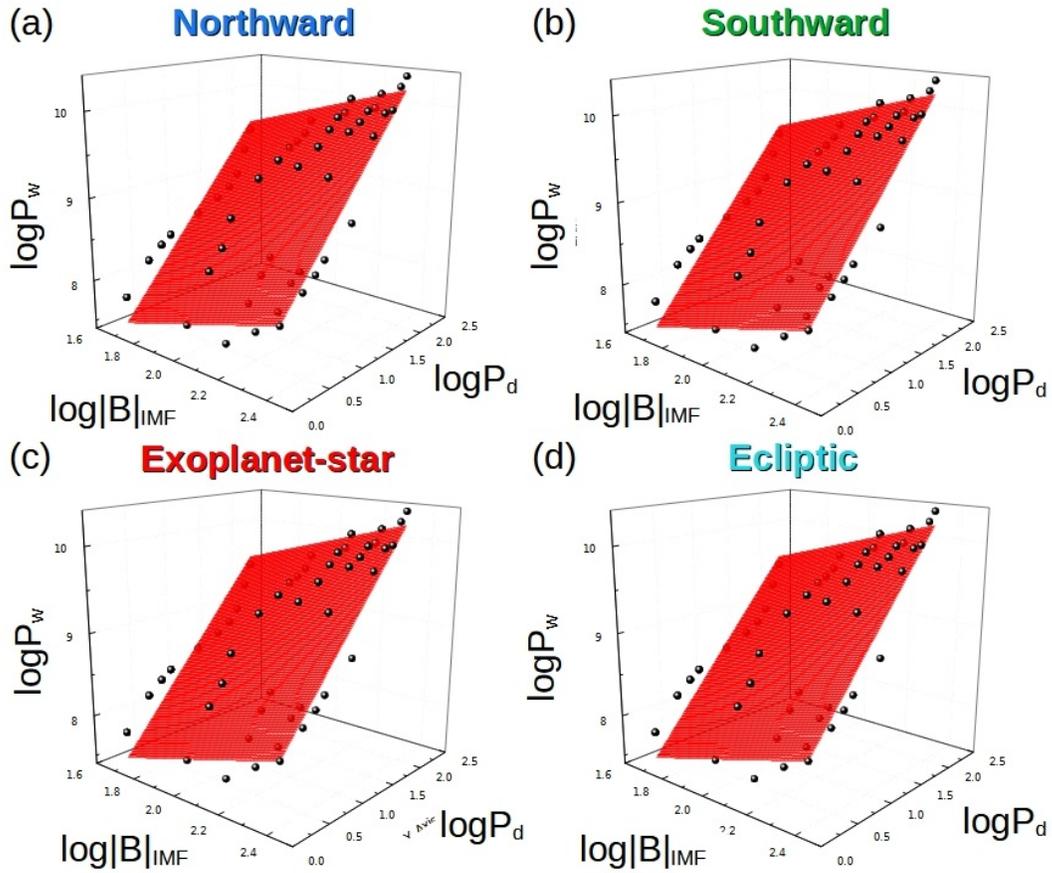


Figure 13. Data fit of the regression $\log P_w \propto \log Z + M \log(|B|_{\text{IMF}}) + N \log(P_d)$ for (a) northward, (b) southward, (c) exoplanet-star and (d) ecliptic IMF.

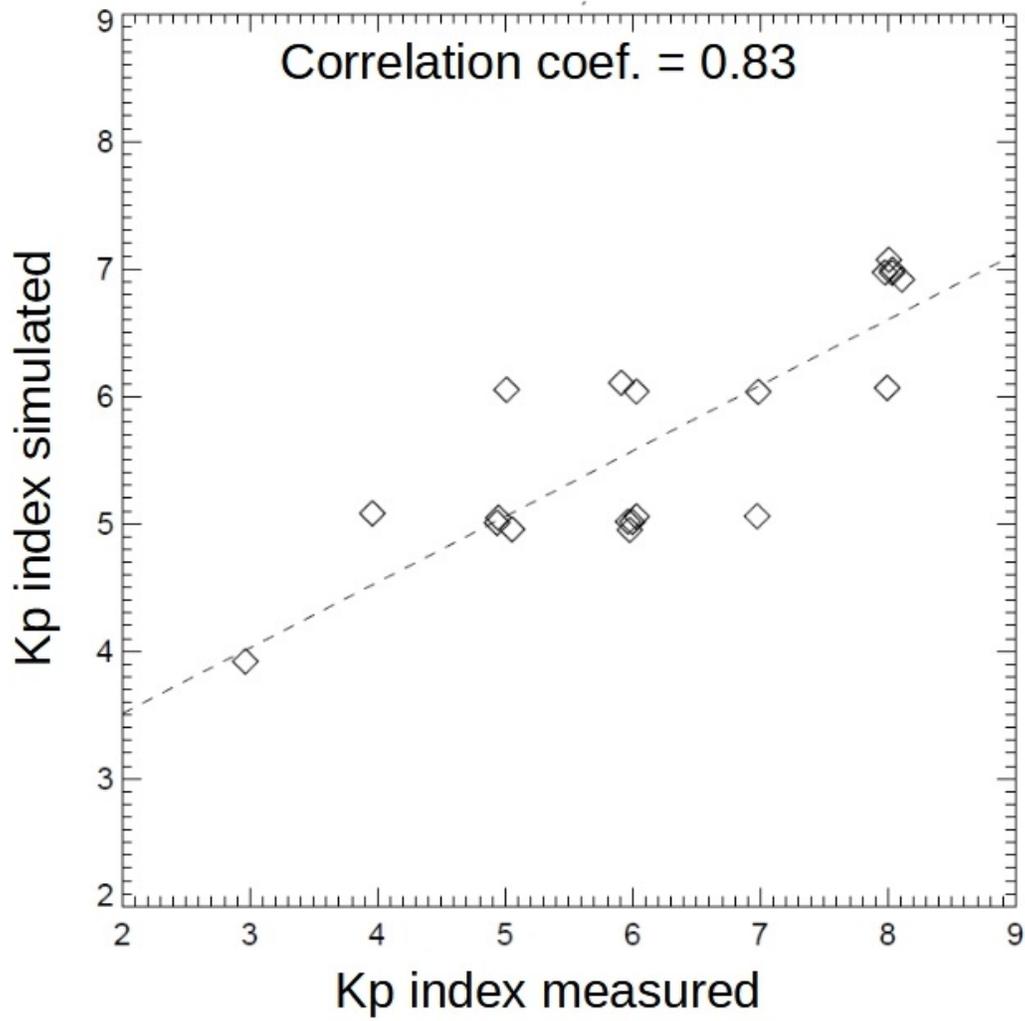


Figure A1. Correlation between the K_p index obtained in the simulations with respect to the measured values.

1 **MHD study of extreme space weather conditions for exoplanets**
2 **with Earth-like magnetospheres: On habitability conditions and**
3 **radio-emission**

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12 **Key Points:**

- 13 • Space weather
14 • Habitability conditions
15 • Radio emission
16 • M stars
17 • F stars

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Abstract

The present study aims at characterizing the habitability conditions of exoplanets with an Earth-like magnetosphere inside the habitable zone of M stars and F stars like τ Boo, caused by the direct deposition of the stellar wind on the exoplanet surface if the magnetosphere shielding is inefficient. In addition, the radio emission generated by exoplanets with a Earth-like magnetosphere is calculated for different space weather conditions. The study is based on a set of MHD simulations performed by the code PLUTO reproducing the space weather conditions expected for exoplanets orbiting the habitable zone of M stars and F stars type τ Boo. Exoplanets hosted by M stars at 0.2 au are protected from the stellar wind during regular and CME-like space weather conditions if the star rotation period is slower than 3 days, that is to say, faster rotators generate stellar winds and interplanetary magnetic fields large enough to endanger the exoplanet habitability. Exoplanets hosted by a F stars type τ Boo at ≥ 2.5 au are protected during regular space weather conditions, but a stronger magnetic field compared to the Earth is mandatory if the exoplanet is close to the inner edge of the star habitable zone (2.5 au) to shield the exoplanet surface during CME-like space weather conditions. The range of radio emission values calculated in the simulations are consistent with the scaling proposed by ? (?) during regular and common CME-like space weather conditions. If the radio telescopes measure a relative low radio emission signal with small variability from an exoplanet, that may indicate favorable exoplanet habitability conditions with respect to the space weather states considered and the intrinsic magnetic field of the exoplanet. The radio emission power calculated for exoplanets with an Earth-like magnetosphere inside the star habitable zone is in the range of $3 \cdot 10^7$ to $2 \cdot 10^{10}$ W if the space weather conditions lead to SW dynamic pressures between 1.5 to 100 nPa and IMF intensities between 50 - 250 nT, and is below the sensitivity threshold of present radio telescopes at parsec distances.

1 Introduction

The space weather effects on the Earth magnetosphere were extensively studied in the last years (? , ? , ? , ?), particularly during extreme events such as intense coronal mass ejections (CME) (? , ? , ?) leading to major perturbations in the Earth magnetosphere structures (? , ? , ? , ?).

The CMEs are solar eruptions produced in the corona due to magnetic reconnections, expelling fast charged particles and a magnetic cloud (? , ? , ? , ?). Extreme space weather events are not exclusive of the Sun or solar-like stars (? , ?), CMEs were also observed in M, K and F type stars (? , ? , ?).

The space weather at the orbit of the Earth and exoplanets depends on the stellar wind (SW) and interplanetary magnetic field (IMF) generated by the host star (? , ? , ?) at their orbital location as well as the conducting and magnetic properties of the local environment. For the case of the Earth, the intrinsic magnetic field is strong enough to avoid the direct precipitation of the SW on the surface even during the largest CMEs observed (? , ? , ? , ?). Extreme space weather conditions occur if the SW dynamic pressures in the range of the 10 to 100 nPa and IMF intensity between 100 and 300 nT.

The space weather in the orbit of exoplanets cannot be compared to the case of the Earth if the host star has characteristics different from the Sun (star type, age, metallicity, ...). If the SW dynamic pressure and IMF intensity generated by the star are large, favorable exoplanet habitability state requires an intrinsic magnetic field strong enough to avoid the direct precipitation of the SW on the exoplanet surface (? , ? , ? , ?). Otherwise, if the protection of the magnetic field is deficient, the exoplanet habitability can be hampered by the effect of the SW as well as the depletion of the atmosphere, especially volatile components such as the water molecules (? , ? , ? , ?). It should be noted that other important factors for the habitability as EUV, X ray and cosmic rays fluxes towards the exoplanet surface are not included in the analysis as such effects are beyond the scope of the present study. Nevertheless, the eventual direct precipitation of the SW must be understood as an important constraint for the habitability of planets.

Exoplanet habitability could be constrained for exoplanet without an intrinsic magnetic field, although the detection and characterization of exoplanet magnetospheres is a challenging topic. It is known from the interaction of the SW with the planets of the solar system that intrinsic magnetic fields are emitters of cyclotron MASER emission at radio wavelengths (??, ??, ??, ??), generated by energetic electrons accelerated in the reconnection region between IMF and the planet magnetic field, flowing towards the planet surface along the magnetic field lines (??). A fraction of the electrons energy is transformed into cyclotron radio emission (??) escaping from the magnetosphere. Such radio emission is detected by ground-based radio telescopes, for example the Nançay decameter array (??), NenuFAR (??) and Low Frequency Array (LOFAR) (??) between others. Likewise, the radio emission detected from an exoplanet magnetosphere could provide information of the exoplanet intrinsic magnetic field (??). Unfortunately, the detection capability of present radio telescopes barely distinguish the radio emission from exoplanets. Recent LOFAR and the Australian Telescope Compact Array (ATCA) measurements tentatively achieved the detection of radio emission from exoplanet systems (??, ??, ??). In addition, radio emission from the red dwarf GJ 1151 was measured, potentially originated in the magnetic interaction with a exoplanet with approximately the size of the Earth (??, ??, ??, ??). Next generation of radio telescopes may be able to detect exoplanet radio emissions at a distances of 20 parsec (??, ??, ??, ??), for example the Square Kilometre Array (SKA) (??), depending on the space weather conditions generated by the host star and the properties of the exoplanet magnetic field.

This study is the continuation of a research activity dedicated to analyze numerically the interaction of the stellar wind with planetary magnetospheres, particularly the radio emission generation with respect to the space weather conditions and the properties of the planet intrinsic magnetic field. First, the radio emission from the Hermean magnetosphere was analyzed in ? (?), showing the important role of the IMF intensity, IMF orientation and SW dynamic pressure on the radio emission generated. Then, ? (?) was dedicated to study the radio emission from exoplanets with different intrinsic magnetic field configurations, identifying a critical dependency between magnetosphere topology and radio emission. Next, ? (?) analyzed the effect of extreme space weather conditions on the Earth magnetosphere. The aim of the present study is to analyze the effect of the space weather conditions on the magnetosphere of exoplanets orbiting the habitable zone of M and F stars. In addition, the radio emission generated from the exoplanet magnetosphere is estimated. The analysis consist in a set of MHD simulations assuming the exoplanet magnetic field is identical to the Earth magnetic field, reproducing the space weather conditions inside the habitable zone of M and F stars.

This paper is structured as follows. Section 2 presents the description of the numerical model. Section 3 introduces the analysis of the space weather effects on the magnetosphere of exoplanet orbiting the habitable zone of M and F stars. Section 4 presents the characterization of the radio emission generated by exoplanets with an Earth-like magnetosphere during extreme space weather conditions. Section 5 discusses and concludes the analysis results.

2 Numerical model

This study is performed using the ideal MHD version of the open-source code PLUTO in spherical coordinates. The model calculates the evolution of a single-fluid polytropic plasma in the nonresistive and inviscid limit (??). A detailed description of the model equations, boundary conditions and upper ionosphere model can be found in (??).

The interaction of the SW with planetary magnetospheres can be studied using different numerical models; present study uses a single fluid MHD code (??, ??, ??, ??, ??). The validity of MHD code results were checked by comparing the simulation results with ground-based magnetometers and spacecraft measurements (??, ??, ??, ??). The study was performed using the single-fluid MHD code PLUTO in spherical 3D coordinates (??). The model was applied successfully to study the global structures of the Hermean magnetosphere (??, ??, ??, ??).

119 ?, ?), the radio emission from exoplanets (?, ?) and the effect of extreme space weather con-
 120 ditions on the Earth magnetosphere (?, ?).

121 The simulations use a grid of 128 radial points, 48 in the polar angle θ and 96 in the
 122 azimuthal angle ϕ , equidistant in the radial direction. The simulation domain is confined be-
 123 tween two concentric shells around the exoplanet, with the inner boundary $R_{in} = 2R_{ex}$ (R_{ex}
 124 the exoplanet radius) and the outer boundary $R_{out} = 30R_{ex}$. The upper ionosphere model ex-
 125 tends between the inner boundary and $R = 2.5R_{ex}$.

126 The exoplanet magnetic field is rotated 90° in the YZ plane with respect to the grid poles
 127 with the aim of avoiding numerical issues (no special treatment was included for the singu-
 128 larity at the magnetic poles). The exoplanet magnetosphere is identical to the Earth magne-
 129 tosphere, thus the tilt of the Earth rotation axis is also included (23° with respect to the eclip-
 130 tic plane).

131 The simulation frame assumed is: z-axis is provided by the planetary magnetic axis point-
 132 ing to the magnetic north pole, star-planet line is located in the XZ plane with $x_{star} > 0$ (so-
 133 lar magnetic coordinates) and the y-axis completes the right handed system.

134 The response of the exoplanet magnetosphere for different SW dynamic pressure (P_d),
 135 IMF intensity ($|B|_{IMF}$) and orientation is calculated based on the data regression obtained by
 136 the set of simulations performed in ? (?) (see Table 5). The SW dynamic pressure is defined
 137 as $P_d = m_p n_{sw} v_{sw}^2 / 2$, with m_p the proton mass, n_{sw} the SW density and v_{sw} the SW veloc-
 138 ity.

139 The effect of different IMF orientations are included in the analysis: Exoplanet-star and
 140 star-exoplanet (also called radial IMF configurations), southward, northward and ecliptic clock-
 141 wise. Exoplanet-star and star-exoplanet configurations indicate an IMF parallel to the SW ve-
 142 locity vector. Southward and northward IMF orientations show an IMF perpendicular to the
 143 SW velocity vector in the XZ plane.

144 **3 Magnetopause standoff distance for exoplanets with an Earth-like magnetic field**

145 This section is dedicated to calculate the magnetopause standoff distance of exoplanets
 146 with an Earth-like magnetic field exposed to different space weather conditions. A detailed de-
 147 scription of the standoff distance calculation in the simulations is shown in the appendix. The
 148 analysis includes regular and CME-like space weather conditions expected for exoplanet or-
 149 biting inside the habitable zone of M and F stars. Consequently, the study provides a first or-
 150 der assessment of the exoplanet habitability with respect to the SW direct deposition on the
 151 exoplanet surface. The analysis is performed assuming exoplanets with an Earth-like magnetic
 152 field because no observational data exists regarding the properties of exoplanets magnetosphere.
 153 Nevertheless, the different IMF orientations tested are equivalent to exoplanets with different
 154 tilt angles.

155 The space weather conditions inside the stellar habitable zone change with the star char-
 156 acteristics (?, ?, ?, ?, ?, ?). The habitable zone for main sequence F stars ($1.1 - 1.5M_{Sun}$)
 157 is located between 2.5 - 5 au (?, ?), G stars ($1.1 - 0.9M_{Sun}$) between 0.84 - 1.68 au (?, ?), K
 158 stars ($0.9 - 0.5M_{Sun}$) between 0.21 - 1.27 au (?, ?) and M stars ($< 0.5M_{Sun}$) between 0.03
 159 - 0.25 au (?, ?). In the following, the habitability conditions imposed by the star in exoplan-
 160 ets at different orbits inside the habitable zone of M and F stars are studied.

161 The habitability conditions obtained in the simulations are defined with respect to the
 162 magnetopause standoff distance above the exoplanet surface. If the normalized standoff dis-
 163 tance is $R_{mp}/R_{ex} = 1$ (R_{mp} is the exoplanet magnetopause standoff distance) there is a direct
 164 precipitation of the SW towards the exoplanet surface. This is the same criteria used in ? (?)
 165 (equations 5 and 6).

Regular SW			
AU	n_{sw} (cm^{-3})	$ v_{sw} $ (km/s)	P_d (nPa)
0.05	2000	540	488
0.1	500	650	177
0.2	90	700	37
CME-like SW			
AU	n (10^3 cm^{-3})	$ v $ (km/s)	P_d (10^3 nPa)
0.05	40	1350	61
0.1	10	1650	23
0.2	1.8	1750	4.6

Table 1. Exoplanet orbit inside the habitable zone of M stars (first column). SW density (second column), velocity (third column) and dynamic pressure (fourth column) for regular and CME-like space weather conditions.

3.1 Exoplanet hosted by M stars

M type stars habitability conditions are an open issue because exoplanets inside the habitable zone are likely to be tidally locked (?, ?, ?) and exposed to a strong radiation from the host star (?, ?) as well as persistent CME events (?, ?, ?). Nevertheless, recent studies indicate tidal locking may constrain but not preclude the habitability conditions of exoplanets (?, ?, ?, ?). Previous studies also assessed the space weather conditions in the orbit of exoplanets inside the habitable zone of M stars (?, ?, ?, ?). Table 1 shows the density, velocity and dynamic pressure of the SW generated by a M star at different orbits following ? (?) SW model for regular and CME-like space weather conditions. The CME-like space weather conditions are guess educated values assuming 20 times the SW density and 2.5 times the SW velocity of the regular space weather conditions. Such parameters are typical for CME conditions for the Sun.

Figure 1 shows the exoplanet habitability constrain imposed by the space weather conditions inside the habitable zone of a M star. The graphs indicate the critical IMF intensity and SW dynamic pressure required for the direct SW precipitation towards the exoplanet surface in the equatorial region (for different IMF orientations), that is to say, the space weather conditions leading to a normalized exoplanet magnetopause standoff distance of $R_{mp}/R_{ex} = 1$. It should be noted that the graphs show the data regression obtained by the simulation performed in ? (?), dedicated to calculate the Earth magnetopause standoff distance for different values of the SW dynamic pressure, IMF intensities and IMF orientations. The range of SW dynamic pressure and IMF intensity values included in the study correspond to regular (panel a) and CME-like (panel b) space weather conditions. The horizontal dashed lines indicate the SW dynamic pressure at the orbit of an exoplanet at 0.05 au (red), 0.1 au (orange) and 0.2 au (blue) from the host star based on ? (?) SW model, providing a reference value of the critical IMF intensity required for the direct SW precipitation onto the exoplanet surface for different IMF orientations based on the pressure balance (see appendix).

During regular space weather conditions, panel a, the critical IMF intensity for an exoplanet at 0.2 au is $|B|_{IMF} > 5000 \text{ nT}$, $\approx 2050 \text{ nT}$ at 0.1 au and $\approx 1100 \text{ nT}$ at 0.05 au if the IMF is southward. The southward IMF is highlighted along the article because it is the IMF orientation leading to the lowest magnetopause standoff distance (maximum reconnection) for a fixed IMF intensity. Consequently, the magnetic field generated by M stars must be very large to threaten the exoplanet habitability. Nevertheless, the magnetic field of young

AU	P_{rot} (days)	n_{sw} (cm^{-3})	$ v_{sw} $ (km/s)	P_d (nPa)	$ B _{IMF}$ (10^3 nT)
0.05	24	4500	280	295	2.16
0.05	12	4500	360	488	17.7
0.05	6	4500	400	602	25.9
0.05	3	4500	450	762	30.3
0.1	24	900	350	92.2	0.54
0.1	12	900	440	146	4.43
0.1	6	900	510	196	6.46
0.1	3	900	620	289	7.57
0.2	24	240	410	33.7	0.31
0.2	12	240	500	50.2	1.11
0.2	6	240	590	69.9	1.62
0.2	3	240	800	128	1.89

Table 2. Exoplanet orbit inside the habitable zone of M stars (first column). Star rotation period (second column). SW density (third column), velocity (forth column) and dynamic pressure (fifth column). IMF intensity (sixth column).

198 and fast rotating M stars can overcome such IMF intensity thresholds (?, ?, ?) reaching val-
199 ues up to 4 kG. The IMF intensity threshold during a CME largely decreases compared to reg-
200 ular space weather conditions, panel b. If the exoplanet orbit is at 0.2 au, the critical $|B|_{IMF} \approx$
201 310 nT for a southward IMF and ≈ 1100 nT for a star-exoplanet IMF. If the exoplanet is at
202 0.1 au, $|B|_{IMF} \approx 110$ nT for a southward IMF, ≈ 500 nT for a star-exoplanet IMF and ≈ 3750
203 nT for a northward IMF. If the exoplanet is at 0.05 au, $|B|_{IMF} \approx 60$ nT for a southward IMF,
204 ≈ 325 nT for a star-exoplanet IMF and ≈ 2100 nT for a northward IMF. That is to say, ex-
205 oplanets at 0.2 au are efficiently protected during CME space weather conditions if the inten-
206 sity of the magnetic field generated by the M star is not strong enough to exceed 310 nT. On
207 the other hand, exoplanets at ≤ 0.1 au are exposed to the direct SW precipitation during CMEs
208 if the IMF intensity exceeds 110 nT. In summary, exoplanets at 0.2 au should be protected from
209 the direct precipitation of the SW by an Earth-like magnetic field, thus the exoplanets is hab-
210 itable with respect to the SW shielding. It should be noted that present study conclusions are
211 consistent with respect to configuration subsets analyzed by other authors (?, ?, ?).

212 As it was mentioned in the previous paragraph, the space weather conditions change with
213 the rotation rate of the star, because the magnetic activity and the properties of the SW gen-
214 erated by the star change (?, ?). The SW velocity during regular space weather conditions is
215 2 times larger if the star rotation is 4 times faster, although the SW density and temperature
216 is weakly affected (?, ?). In addition, faster rotators have a stronger magnetic activity, because
217 the large-scale surface magnetic field ($B_{surf,*}$) dependency with the Rossby number (R_o) is $B_{surf,*} \propto$
218 $R_o^{-1.3}$ (?, ?, ?). Thus the IMF intensity at the exoplanet orbit is higher as well as the CME fre-
219 quency and intensity (?, ?, ?). Consequently, if the effect of the M star rotation period is in-
220 cluded in the analysis, the threshold of the IMF intensity and SW dynamic pressure for the
221 direct precipitation of the SW toward the exoplanet surface changes. Table 2 indicates the SW
222 density and velocity in the orbit of an exoplanet at 0.05, 0.1 and 0.2 au from the host M star
223 for different rotation periods (P_{rot}) for the star during regular space weather conditions (data
224 derived from ? (?) simulations). The SW density has a weak dependency with the star rota-
225 tion but the SW velocity and IMF intensity increases with the star rotation. The range of M
226 star rotation periods analyzed include the majority of the 795 M stars identified by Kepler mis-
227 sion as a sub-sample of the 12000 main sequence stars identified (?, ?). Nevertheless, recent
228 surveys of M star identified an important population of slow M stars rotators, showing rota-
229 tion periods between 30 to 120 days (?, ?, ?).

Figure 2 indicates the IMF intensity and SW dynamic pressure threshold with respect to the M star rotation rate for regular space weather conditions.

The model shows a large decrease of the IMF intensity threshold if the M star rotation period decreases given a SW dynamic pressure. $\Delta|B|_{IMF}$ is indicated by the bold arrows in the top of the graph for each IMF orientation between the cases of star with rotation rates of 24 and 3 days. For an exoplanet at 0.05 au, the IMF intensity threshold decreases from 1500 nT to 850 nT reducing the star rotation period from 24 to 3 days if the IMF is southward, as well as from 3000 nT to 2000 nT if the IMF is in the exoplanet-star orientation. Regarding an exoplanet orbit at 0.1 au, the IMF intensity threshold decreases from 3250 nT to 1500 nT for a southward IMF, as well as from 4750 nT to 3000 nT for an exoplanet-star IMF. If the exoplanet orbit is located at 0.2 au, the IMF intensity threshold decreases from 5550 nT to 2600 nT for a southward IMF and from 7000 nT to 4250 nT for an exoplanet-star IMF. The IMF intensity threshold obtained can be compared with the magnetic field generated by M stars at different orbits following ? (?) simulations (last column of table 2). At 0.05 au, the IMF intensity is above the threshold for a Southward IMF orientation if the star rotation period is shorter than 24 days, and below the threshold for an exoplanet-star IMF if the rotation period is 24 days or larger. That is to say, favorable habitability conditions with respect to SW of an exoplanet at 0.05 au require an intrinsic magnetic field stronger than Earth's if the rotation rate of the M star is 24 days or smaller. At 0.1 au, the IMF intensity is above the threshold for Southward and exoplanet-star IMF orientation and the rotation rate is 12 days or faster. Thus, exoplanets at 0.1 au require a magnetic field stronger than the Earth if the host M star rotation rate is smaller than 12 days. If the exoplanet is at 0.2 au, the IMF intensity is below the threshold for all IMF orientations if the star rotation rate is 3 days or slower, so an Earth-like magnetic field can efficiently shield the exoplanet surface.

Summarizing, exoplanets with an Earth-like magnetic field hosted by a M star and located at 0.2 au are shielded from the SW during regular and CME-like space weather conditions. In addition, such protection holds for M stars with rotation periods as fast as 3 days during regular SW space weather conditions. Nevertheless, fast rotating M stars with strong and recurrent CME-like events can restrict the exoplanet habitability conditions. On the other hand, exoplanets at 0.1 au are shielded from regular and CME-like space weather conditions only if the M stars rotation period is 12 days or larger. Finally, exoplanets at 0.05 au are vulnerable during CME-like events even for M stars with the a rotation period of 24 days, thus exoplanet habitability requires a magnetic field stronger with respect to the Earth. Nevertheless, exoplanet at 0.05 au hosted by slower rotators with $P_{rot} > 24$ days are protected during standard and CME-like events by an Earth-like magnetic field if the IMF intensity is lower than 1000 nT for a southward IMF.

3.2 Exoplanet hosted by F stars type τ Boo

Space weather conditions in F stars were analyzed in previous studies, particularly for τ Boo type *F7V*, concluding the SW may have a density 135 times larger with respect to the SW generated by the Sun, as well as a velocity around 300 km/s (?). Table3 shows guess educated values of the space weather conditions in the orbit of an exoplanet hosted by a F star similar to τ Boo near the bottom and upper range of the habitable zone. The SW density during regular space weather conditions is assumed 100 times the SW density generated by the Sun at 2.5 and 5 au. The velocity is the same with respect to (?), 300 km/s at 2.5 au. In addition, an extrapolation is assumed to characterize the space weather conditions during CMEs, selecting a SW density 20 times larger and a velocity 5 times higher with respect to the regular space weather conditions.

Figure 3 indicates the critical IMF intensity and SW dynamic pressure required for the direct SW precipitation towards an exoplanet hosted by a F star type τ Boo inside the habitable zone during CME-like space weather conditions. The same analysis for regular space weather conditions is not included because the IMF intensity and SW dynamic pressure are

Regular SW			
AU	n_{sw} (cm^{-3})	$ v_{sw} $ (km/s)	P_d (nPa)
2.5	50	300	3.8
5.0	20	310	1.6
CME-like SW			
AU	n (10^3 cm^{-3})	$ v_{sw} $ (10^3 km/s)	P_d (10^3 nPa)
2.5	1.0	1.5	1.88
5.0	0.4	1.55	0.8

Table 3. Exoplanet orbit inside the habitable zone of F star type τ Boo (first column). SW density (second column), velocity (third column) and dynamic pressure (fourth column) for regular and CME-like space weather conditions.

281 well below the threshold required for the direct SW precipitation, that is to say, the exoplanets
282 at 2.5 – 5.0 au are shielded during regular space weather conditions.

283 Exoplanets located at 5 au show an IMF intensity threshold of $|B|_{IMF} \approx 825$ nT for a
284 southward IMF and $|B|_{IMF} \approx 2300$ nT for an exoplanet-star IMF. Regarding exoplanets at
285 2.5 au, the IMF intensity threshold is $|B|_{IMF} \approx 500$ nT for a southward IMF and $|B|_{IMF} \approx$
286 1550 nT for an exoplanet-star IMF. It must be noted the magnetic activity of τ Boo is larger
287 with respect to the Sun, showing a shorter magnetic cycle of 2 years (?, ?, ?). It is known that
288 F stars have a slower decrease of the rotation rate along the main sequence, leading to a stronger
289 magnetic field compared to G stars (?, ?, ?) with the exception of low mass stars populations
290 ($< 0.9M_{Sun}$) that maintain rapid rotation for much longer than solar-mass stars (?, ?). Con-
291 sequently, the effect of the CME on exoplanets orbiting inside the habitable zone of F star, par-
292 ticular τ Boo, can increase the exoplanet habitability conditions if the frequency of these ex-
293 treme space weather events is high.

294 Next step of the analysis is to include the effect of stellar rotation. The F star rotation
295 period is lower with respect to less massive stars such as G, K and M stars. The lower bound
296 is around 2 days for $F0$ stars increasing to 10 days for $F9$ stars (?, ?). Table 4 indicates guess
297 educated values of the SW dynamic pressure and IMF intensity at different exoplanet orbits
298 for different F star rotation periods during CME space weather conditions. The values of the
299 IMF intensity are extrapolated from observational data of F stars magnetic field magnitude (?,
300 ?, ?, ?, ?) and modeling results (?, ?). We assume the SW velocity increases with the star
301 rotation although the SW density and temperature is constant, extrapolating ? (?) results.

302 Figure 4 indicates the IMF intensity and SW dynamic pressure threshold with respect
303 to the F star rotation rate for CME-like space weather conditions.

304 The simulations indicate the habitability of exoplanets at 2.5 au from the host F star is
305 conditioned by the SW if the star rotation period is shorter than 10 days. The exoplanet sur-
306 face is protected if the star rotation period is 10 days or above, showing an IMF intensity of
307 500 nT that is smaller compared to the IMF intensity required for the direct SW precipitation
308 . For a stellar rotation of 7.5 or 5 days, direct SW precipitation exists during a southward IMF
309 with 675 and 575 nT, respectively, smaller than the IMF intensity during CMEs. The IMF thresh-
310 old for the direct SW precipitation is also largely exceeded if the star rotation is 2 days for
311 an IMF oriented in the Southward or Exoplanet-star directions. Consequently, exoplanets at
312 2.5 au requires an intrinsic magnetic field intensity stronger with respect to the Earth if the

AU	P_{rot} (days)	n_{sw} (10^3 cm^{-3})	$ v_{sw} $ (10^3 km/s)	P_d (10^3 nPa)	$ B _{IMF}$ (10^3 nT)
2.5	2	1.0	1.7	2.4	3
2.5	5	1.0	1.3	1.4	1.5
2.5	7.5	1.0	1.15	1.1	1
2.5	10	1.0	1.0	0.8	0.5
5.0	2	0.4	1.75	1.0	0.75
5.0	5	0.4	1.35	0.6	0.4
5.0	7.5	0.4	1.2	0.5	0.25
5.0	10	0.4	1.05	0.4	0.1

Table 4. Exoplanet orbit inside the habitable zone of F star (first column). Star rotation period (second column). SW density (third column), velocity (forth column) and dynamic pressure (fifth column). IMF intensity (sixth column).

313 star rotation period is smaller than 10 days. On the other hand, the simulations show that ex-
 314 oplanets with orbits at 5.0 au are protected during CME-like space weather conditions if the
 315 star rotation period is above 2 days. In the case of the rotation period is 2 days the IMF in-
 316 tensity threshold is similar to the IMF intensity during CMEs (around 25 nT smaller).

317 In summary, regular space weather conditions does not impact the habitability of exo-
 318 planets in the habitable zone of F stars type τ Boo. On the other hand, persistent and strong
 319 CME events can largely influence the habitability of exoplanets nearby the inner boundary of
 320 the habitable zone, thus a stronger magnetic field regarding the Earth magnetic field is manda-
 321 tory. Nevertheless, exoplanets at the outer region of the habitable zone could be efficiently shielded
 322 by an Earth-like magnetic field. The analysis of the star rotation effect on the habitability state
 323 due to the SW indicates that exoplanets with an Earth-like magnetic field at 5.0 au are effi-
 324 ciently protected during extreme space weather conditions if the star rotation period is larger
 325 than 2 days. On the other hand, exoplanets at 2.5 au requires an intrinsic magnetic field stronger
 326 regarding the Earth if the star rotation period is smaller than 10 days. It should be noted that
 327 the rotation period of τ Boo is 3.3 days, thus habitability conditions due to the space weather
 328 require an exoplanet magnetic field stronger compared to the Earth. That means, habitability
 329 conditions may relax for the case of F stars in the spectral range from $F7$ to $F9$ because the
 330 rotation period is larger (10 days or higher) (?). Nevertheless, the habitable zone of $F7$ to
 331 $F9$ stars displaces closer to the star, located between 1.1 to 2.5 au. Consequently, exoplanets
 332 located in the outer region of the habitable zone of $F7$ to $F9$ stars require, at least, a magnetic
 333 field similar to the Earth to avoid the direct SW precipitation during CMEs, although it must
 334 be stronger if the orbit is closer to the star or the star rotation period is shorter than 10 days.

335 4 Radio emission from exoplanets with an Earth-like magnetosphere

336 Radio emission from exoplanet magnetospheres and space weather conditions are closely
 337 connected. Radio emission measurements may provide information of the exoplanet magnetic
 338 field and, once the characteristics of the exoplanet magnetic field are inferred, insights about
 339 the space weather conditions generated by the host star on the exoplanet orbit. This section
 340 is dedicated to the analysis of the influence of the space weather conditions, from regular to
 341 CME-like, on the radio emission generation, providing simplified new tools for the interpre-
 342 tation of radio telescopes observational data.

343 The interaction of the SW with a planetary magnetosphere can be analyzed using the
 344 analogous of a flow facing a magnetized object, leading to the partial transfer of the flow en-
 345 ergy. The transferred energy is transformed to radiation and the radiation power (P_{disp}) is pro-
 346 portional to the intercepted flux of the magnetic energy. Thus, following the radio-magnetic

347 Bode's law, the incident magnetized flow power and the obstacle magnetic field intensity can
 348 be used to approximate the radio emission as $P_w = \beta[P_{disp}]^n$, with P_w the radio emission power,
 349 β the efficiency of dissipated power to radio emission conversion with $n \approx 1$ (? , ? , ?) and $\beta \approx$
 350 $2 \cdot 10^{-3} - 10^{-2}$ (? , ?).

The power dissipated in the interaction between the SW with the magnetosphere is calculated at the exoplanet day side. Irreversible processes in the interaction convert internal, bulk flow kinetic and magnetic energy into the kinetic energy required to accelerate the electrons along the magnetic field lines, and leading to cyclotron-maser radiation emission by these accelerated electrons. The energy transfer can be evaluated analyzing the energy fluxes of the system. There is a detailed discussion of the flux balance in ? (?). The radio emission is calculated using the net magnetic power deposited on the exoplanet day side (? , ? , ? , ?):

$$P_w = 2 \cdot 10^{-3} P_B = 2 \cdot 10^{-3} \int_V \vec{\nabla} \cdot \frac{(\vec{v} \wedge \vec{B}) \wedge \vec{B}}{\mu_0} dV$$

351 with P_B the divergence of the magnetic Poynting flux associated with the hot spots of energy
 352 transfer in the exoplanet day side and V the volume enclosed between the bow shock nose and
 353 the magnetopause.

354 In the following, the radio emission is calculated during regular and CME-like space weather
 355 conditions, modifying the SW dynamic pressure as well as IMF intensity and orientation of
 356 the model. First, the effect of the SW dynamic pressure and IMF intensity on the radio emission
 357 is analyzed separately. Next, the trends of the radio emission with respect to the SW dynamic
 358 pressure and IMF intensity are evaluated together.

359 4.1 Effect of the SW dynamic pressure

360 This section is dedicated to the study of the exoplanet radio emission generation with
 361 respect to the SW density and velocity, hence the SW dynamic pressure. Particular emphasis
 362 is dedicated to clarify the link between bow shock compression and radio emission generation.
 363

364 Figure 5 shows the logarithm of the radio emission power at the exoplanet day side for
 365 a set of SW dynamic pressure values increasing the SW velocity (fixed the SW density to 12
 366 cm^{-3} , panel a) and increasing the SW density (fixed the SW velocity to 350 km/s, panel b)
 367 for a star-exoplanet IMF orientation with $|B|_{IMF} = 10$ nT. Simulations with $P_d < 10$ nPa
 368 are analyzed separately due to the effect of the magnetosphere thermal pressure on the mag-
 369 netopause standoff distance, negligible in the simulations with $P_d \geq 10$ nPa (? , ?).

370 The radio emission increases from 10^6 to 10^{10} W as the SW increases from regular to
 371 super CME-like space weather conditions. The order of magnitude of the radio emission power
 372 calculated in the simulations is consistent with ? (?) scaling (around $6 \cdot 10^7$ W) for SW ve-
 373 locity values between $500 - 1200$ km/s ($P_d = 2.5 - 14$ nPa) and SW density values between
 374 $30 - 120$ cm^{-3} ($P_d = 3.1 - 13.3$ nPa), that is to say, the radio emission values obtained from
 375 the simulations and the scaling are similar for regular space weather conditions. If $P_d < 2.5$
 376 nPa, the radio emission power is below 10^7 W. For common CME-like conditions ($15 < P_d <$
 377 40 nPa) the radio emission power increases up to $6 \cdot 10^8$ W. During strong CME-like space
 378 weather conditions ($40 < P_d < 100$ nPa) the radio emission power reaches 10^9 W. For su-
 379 per CME-like space weather conditions ($P_d > 100$ nPa) the radio emission power is $2 \cdot 10^9$
 380 W. The enhancement of the radio emission as P_d increases is caused by a higher net magnetic
 381 power dissipation at the exoplanet day side as the magnetosphere compression intensifies.

382 Next, the trends of the radio emission with respect to the SW density and velocity are
 383 analyzed. Figure 6, panels a and c, show the fit of the radio emission power to the square value
 384 of the SW velocity $P_w \propto \Gamma(v_{sw}^2)^\alpha$ if $P_d \leq 10$ nPa and > 10 nPa, respectively. Figure 6, pan-
 385 els b and d, show the fit of the radio emission power to the SW density $P_w \propto \Gamma(n_{sw})^\alpha$ if $P_d \leq$
 386 10 nPa and > 10 nPa, respectively. The radio emission trends are analyzed separately in the

$P_d \leq 10$ (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

Table 5. Regression parameters in simulations with different SW velocity and density values. (a) Variable SW parameter in the data regression, (b) Γ factor and (c) α exponent. Trends in the simulations with $P_d \leq 10$ nPa and $P_d > 10$ nPa are analyzed separately.

387 simulations with $P_d \leq 10$ nPa and > 10 nPa to isolate the effect of the thermal pressure caused
 388 by the magnetosphere (for more information please see ? (?)). The parameters of the data re-
 389 gression are indicated in table 5.

The data fit finds similar exponents for the regression $P_w \propto (v_{sw}^2)^\alpha$ and $P_w \propto (n_{sw})^\alpha$ if $P_d \leq 10$ nPa, that is to say, proportional to the SW dynamic pressure. The scaling of the radio emission with respect to the SW dynamic pressure is stronger in simulations with $P_d > 10$ nPa, thus the radio emission generation is further promoted in a compressed magnetosphere. This is explained by the enhancement of the Poynting flux divergence as the magnetopause is located closer to the exoplanet surface. The regression parameters can be compared with the theoretical expression of the radio emission induced by a magnetized flow dominated by the dynamic pressure facing a magnetized obstacle (?, ?, ?):

$$P_W = \beta \frac{|B_{IMF,\perp}|^2 B_{ex}^{2/3}}{\mu_0^{4/3}} \left(\frac{v_{sw}}{m_p n_{sw}} \right)^{1/3} R_{ex}^2 \pi \frac{2.835}{K^{1/3}}$$

390 with $B_{IMF,\perp}$ the perpendicular component of the IMF with respect to the flow velocity, B_{ex} the
 391 intensity of the magnetic field in the equator of the magnetized obstacle, μ_0 the vacuum mag-
 392 netic permeability and $K = 1-2$. Here, the intercepted flux of magnetic energy is estimated
 393 as $P_{disp} = \epsilon (v_{sw} |B_{IMF,\perp}|^2 / \mu_0) \pi R_{obs}^2$ with $\epsilon = M_A / (1 + M_A^2)^{1/2}$ (M_A Alfvénic Mach number),
 394 $R_{obs} = 1.5 R_{mp}$ and $R_{mp} = R_{ex} (2 B_{ex} / (\mu_0 K n_{sw} v_{sw}^2))^{1/6}$. Thus, the theoretical dependency of
 395 the radio emission power with the SW velocity is $v_{sw}^{0.33}$ and with the SW density is $n_{sw}^{-0.33}$. The
 396 radio emission calculated in the simulations (all dominated by the SW dynamic pressure be-
 397 cause $P_{IMF} = 0.09$ nPa) shows a stronger dependency with the SW velocity compared to the
 398 theoretical model. Regarding the SW density, the simulations show a direct proportionality with
 399 the radio emission, not an inverse proportionality as the theoretical expression predicts. This
 400 discrepancy can be explained by the enhancement of the magnetosphere compression and bow
 401 shock distortion as the SW dynamic pressure increases, that is to say, the theoretical expres-
 402 sion cannot reproduce the effect of the bow shock compression associated with a modifica-
 403 tion of the energy fluxes, net magnetic power dissipated and divergence of the magnetic Poynt-
 404 ing flux in the magnetosphere day side. Thus, the theoretical scaling law could underestimate
 405 the radio emission power generated in exoplanets for space weather conditions leading to a
 406 strongly compressed bow shock.

407 The effect of the SW dynamic pressure on the radio emission generation is highlighted
 408 in figure 7, comparing the divergence of the Poynting flux in the bow shock and magnetopause
 409 region for simulations with $v_{sw} = 300$ km/s ($P_d = 0.9$ nPa) and $v_{sw} = 3000$ km/s ($P_d = 90$
 410 nPa). The Poynting flux divergence is more than one order of magnitude higher in the sim-
 411 ulation with $P_d = 90$ nPa, explaining the radio emission enhancement as the SW dynamic
 412 pressure increases. It should be noted that the maxima of the Poynting flux divergence is lo-

413 cated closer to the exoplanet surface as P_d increases because the magnetosphere standoff dis-
 414 tance is smaller. In addition, the local maxima of the Poynting flux divergence is displaced
 415 towards the South of the magnetosphere in both simulations, determined by the IMF orien-
 416 tation and in particular by the location of the reconnection region. From the observational point
 417 of view, radio telescopes may measure a signal with a more localized radio emission maxima
 418 as the bow shock compression enhances, although the radio emission maxima should be more
 419 diffused as the bow shock compression is weakened.

420 **4.2 Effect of the IMF intensity and orientation**

421 In this subsection we analyze the effect of the IMF intensity and orientation on the ex-
 422 oplanet radio emission generation. In particular, the role of the reconnection between the IMF
 423 and the exoplanet magnetic field is explored, as well as the bow shock formation or disper-
 424 sion as the SW dynamic pressure or the IMF magnetic pressure dominate, respectively.

425 The IMF can induce large distortions in the exoplanet magnetic field, modifying locally
 426 the topology of the magnetosphere, particularly in the reconnection regions between the ex-
 427 oplanet magnetic field and the IMF. Figure 8 shows the logarithm of the radio emission fixed
 428 $P_d = 1.2$ nPa for different IMF orientations (exoplanet-star, northward, southward and eclip-
 429 tic) and IMF intensities between 10 and 250 nT.

430 The same order of magnitude is obtained for the radio emission power comparing sim-
 431 ulation results and ? (?) scaling if the IMF intensity is between 20 - 125 nT for an exoplanet-
 432 star IMF, 10 - 125 nT for a northward IMF, 10 - 50 nT for a southward IMF and 10 - 70 nT
 433 for an ecliptic IMF. Consequently, the radio emission calculated in the simulations and the val-
 434 ues predicted by the scaling are similar from regular to strong CME-like space weather con-
 435 ditions regarding the IMF intensity. The simulations also predict a radio emission power above
 436 10^8 W during Super CME. The IMF orientation leading to the largest radio emission is the
 437 southward IMF, followed by the ecliptic and exoplanet-star IMF. The lowest radio emission
 438 is observed for the northward IMF. The variation of the radio emission values regarding the
 439 IMF orientation is explained by the location and intensity of the reconnection regions. The south-
 440 ward IMF orientation induces the strongest reconnection, located in the equatorial region of
 441 the magnetosphere leading to the smallest magnetopause standoff distance and the largest ra-
 442 dio emission. Likewise, the northward IMF orientation causes the lowest radio emission be-
 443 cause the reconnection region is located nearby the exoplanet poles and the magnetopause stand-
 444 off distance is larger regarding the other IMF orientations. It should be noted that the loca-
 445 tion of the radio emission maxima and the reconnection regions are concomitant in the sim-
 446 ulation, thus the radio emission maxima displaces with the reconnection region as the IMF in-
 447 tensity increases; towards the equatorial region for a southward IMF, the poles for a northward
 448 IMF, to the South of the magnetosphere for a star-exoplanet IMF, to the North for a exoplanet-
 449 star and tilted to a higher longitude for a IMF oriented in the equatorial plane.

450 Figure 9 shows the Poynting flux divergence in the bow shock and magnetopause region
 451 for simulations with an exoplanet-star IMF with $|B|_{IMF} = 30$ nT (panel a) and 250 nT (panel
 452 b). The radio emission is more than one order of magnitude larger in the simulation with $|B|_{IMF} =$
 453 250 nT.

454 The effect of the IMF orientation on the radio emission is larger in simulations with $|B|_{IMF} \geq$
 455 70 nT. On the other hand, simulations with $|B|_{IMF} < 70$ nT show similar radio emission val-
 456 ues for all the IMF orientations. This is explained by the absence of the bow shock in the sim-
 457 ulations with $|B|_{IMF} \geq 70$ nT, because the Alfvénic Mach number $M_A = v_{sw}/v_A < 1$ (v_A is
 458 the Alfvén speed). Simulations with $|B|_{IMF} < 70$ nT ($M_A > 1$) lead to the formation of the
 459 bow shock, showing two regions with a local maxima of the Poynting flux divergence: 1) the
 460 reconnection region between the IMF and the exoplanet magnetic field, 2) the nose of the bow
 461 shock where the IMF lines are compressed and bent. Figure 10 shows the radio emission from
 462 the bow shock nose, panel a, and the reconnection regions, panel b, for a simulation with south-
 463 ward IMF and $|B|_{IMF} = 30$ nT. The compression and bending of the IMF lines lead to a lo-

$M_A > 1$		
IMF	Γ	α
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

Table 6. Regression parameters in simulations with different IMF orientations and intensities. IMF orientation (first column), Γ factor (second column) and α exponent (third column). The trends in simulations with $M_A > 1$ and $M_A < 1$ are analyzed separately.

464 cal maxima of the Poynting flux divergence in the nose of the bow shock. On the other hand,
 465 the Poynting flux divergence is larger and more localized in the magnetopause region where
 466 the IMF and the exoplanet magnetic field reconnects, closer to the exoplanet surface. Conse-
 467 quently, if the bow shock exists, the Poynting flux divergence in the bow shock depends on
 468 the SW dynamic pressure as well, thus the role of the IMF orientation in the radio emission
 469 generation is smaller. Radio telescopes may measure a signal with well defined radio emis-
 470 sion maxima if the bow shock does not exist, although showing a fast variability of the max-
 471 ima location as the IMF orientation changes.

Figure 11 and table 6 show the fit of the radio emission values calculated in the sim-
 ulations using the regression $P_w \propto \Gamma |B|_{IMF}^\alpha$. It should be noted that the IMF pressure in the
 simulations with $|B| > 50$ nT is larger than the SW pressure ($P_{IMF} > 1.2$ nPa). In such con-
 figurations the theoretical expression of the radio emission is (?, ?, ?):

$$P_W = \beta \frac{v_{sw} |B_{IMF,\perp}|^{4/3}}{\mu_0} R_{ex}^2 B_{ex}^{2/3} 3.6\pi$$

472 Here, $R_{mp} = R_{ex} (2B_{ex}/|B_{IMF,\perp}|)^{1/3}$. Thus, the theoretical dependency of the radio emission
 473 power with the SW velocity is linear with the v_{sw} and a super linear with the intensity of an
 474 IMF perpendicular to the plasma flow. Consequently, the scaling for the simulations with dom-
 475 inant dynamic pressure or dominant IMF pressure must be analyzed separately.

476 The regression exponents indicate the radio emission dependency with the IMF inten-
 477 sity is weaker in simulations with dominant SW pressure compared to simulations with dom-
 478 inant IMF pressure. This is the opposite tendency with respect to the radio-magnetic scaling
 479 law that predicts a stronger $|B|_{IMF}$ trend if the SW pressure is dominant ($|B_{IMF,\perp}|^2$). This in-
 480 consistency can be explained by the effect of the bow shock compression in the simulations.
 481 On the other hand, the regression exponents obtained in simulations with dominant IMF pres-
 482 sure and Southward / Northward IMF orientations are similar to the radio-magnetic scaling
 483 law if the dynamic pressure is dominant ($\alpha \approx 2$). That is to say, radio-magnetic scaling law
 484 and simulation lead to similar trends if the bow shock does not exist and the IMF is perpen-
 485 dicular to the SW velocity. Consequently, deviations appear if the IMF is unaligned with the
 486 exoplanet magnetic field axis and the role of bow shock compression is added in the analy-
 487 sis, effects not included in the radio-magnetic scaling law. In summary, the theoretical scal-
 488 ing law could underestimate the radio emission power generated in exoplanets during space
 489 weather conditions leading to the bow shock dispersion.

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

Table 7. Regression parameters in simulations with different SW dynamic pressure, IMF orientation and intensity. IMF orientation (first column), Z parameter (second column), M parameter (third column) and N parameter (fourth column).

4.3 Combined effect of the SW dynamic pressure, IMF intensity and IMF orientation

The analysis of the combined effect of SW dynamic pressure, IMF intensity and orientation provides an improved approach of the radio emission generation trends, particularly during extreme space weather conditions that melds a large compression of the bow shock and an intense magnetic reconnection.

Figure 12 shows the logarithm of the radio emission with respect to the SW dynamic pressure, IMF intensity and orientation for CME-like space weather conditions ($P_d = 1.5 - 100$ nPa and $|B|_{IMF} = 50 - 250$ nT). It should be noted that the increment of the SW dynamic pressure in the simulations is done by increasing the velocity of the SW, thus the SW density is fixed in the simulations. The radio emission ranges from $3 \cdot 10^8$ W for common CME (20 nPa and 50 nT) to above 10^{10} W for super CME-like space weather conditions (100 nPa and 250 nT). A large bow shock compression (large SW dynamic pressure) combined with a strong reconnection between IMF and exoplanet magnetic field (IMF intensity is high) lead to a further enhancement of the radio emission. The simulations with large SW dynamic pressure show similar radio emission values independently of the IMF intensity and orientation. On the other hand, the radio emission show larger changes between simulations with different IMF intensity and orientation if the SW dynamic pressure is low. Again, this result is consistent with previous analysis because simulations with low SW dynamic pressure and large IMF (particularly if $M_A < 1$) show a larger effect of the IMF intensity and orientation on the radio emission.

Figure 13 and table 7 indicate the data fit and the parameters of the regression $\log P_W \propto \log Z + M \log(|B|_{IMF}) + N \log(P_d)$, respectively. This expression is derived from $P_W \propto Z |B|_{IMF}^M P_d^N$. The data regression includes simulations with dominant SW and dominant IMF pressure because the main part of the space weather conditions analyzed have a dominant SW pressure, indicated by the black dashed line in figure 12 (SW dominant cases above the line).

The regression parameters with respect to the IMF intensity show similar trends compared to simulations with fixed SW dynamic pressure if the bow shock exist ($M \approx 1$ and $\alpha \approx 1$, see table 6 and 7). On the other hand, the scaling with respect to the SW dynamic pressure is weaker compared to simulations with fixed IMF intensity and orientation ($N \approx 1$ although $\alpha \approx 1.8$ if $P_d > 10$ nPa, see table 5 and 7). Consequently, the simulations analysis indicate the effect of the IMF intensity on the radio emission is similar to the SW dynamic pressure if the bow shock exist and it is strongly compressed. In addition, there is a variation of the radio emission scaling with respect to the IMF orientation up to 20%, pointing out the important role of the IMF orientation on the radio emission generation. If the exponents of the data regression are compared to the radio-magnetic scaling law for a dominant SW dynamic pressure, there is clear deviation showing a weaker trend for $|B|_{IMF}$ ($M \approx 1$ versus 2) although stronger for P_d ($N \approx 1$ versus 0.17). Such difference is smaller if the regression exponents are compared to the radio-magnetic scaling law for a dominant IMF pressure, showing a similar $|B|_{IMF}$ exponent ($M \approx 1$ versus 1.33) and a P_d exponent 2 times larger ($N \approx$

1 versus 0.5). Indeed, the best agreement is obtained if the IMF orientation is Southward ($M =$
 1.22 and $N = 0.95$). Consequently, as it was previously discussed, the discrepancy with the
 radio-magnetic scaling law for the configurations with dominant SW pressure could be caused
 by the effect of the bow shock compression.

4.4 Analysis result consequences on the interpretation of radio telescope measurements

The analysis of the radio emission generated in exoplanet magnetospheres for different
 space weather conditions provides useful information regarding the variability of the radio emis-
 sion signal measured by radio telescopes. In addition, an order of magnitude approximation
 of the radio emission generated by exoplanets with an Earth-like magnetosphere is provided
 for different space weather conditions.

The combined effect of a strongly compressed bow shock and an intense reconnection
 between the IMF and the exoplanet magnetic field can lead to a large increase of the radio emis-
 sion generation. For the case of an exoplanet with an Earth-like magnetic field, the radio emis-
 sion can increase more than four orders of magnitude comparing regular and extreme space
 weather conditions (super CME-like events for the case of the Earth).

The simulations indicate that the largest radio emission variability should be observed
 from exoplanets hosted by stars with large magnetic activity and low SW dynamic pressure,
 leading to space weather conditions that avoid the formation of the bow shock. The radio emis-
 sion variation for a given SW dynamic pressure could be close to one order of magnitude re-
 garding the IMF orientation. On the other hand, if the exoplanet is hosted by stars with low
 magnetic activity although large SW dynamic pressure, the variability of the radio emission
 with the IMF orientation should be small and mainly induced by changes on the SW dynamic
 pressure. The variation of the radio emission with the IMF in simulations with bow shock is
 smaller than a factor 1.5.

The study also shows that, if the host star generates a SW with large dynamic pressure
 and an intense IMF, the effect of the IMF orientation should also induce an substantial vari-
 ability on the radio emission signal even if the bow shock exist, close to a factor 2. Conse-
 quently, a large radio emission variability is linked to unfavorable space weather conditions
 because the host star magnetic activity is large, leading to a strong reconnection between IMF
 and exoplanet magnetic field, reducing the magnetopause standoff distance. The same way,
 a strong radio emission signal combined with a small variability indicates a compressed mag-
 netosphere, that is to say, the SW dynamic pressure generated by the host star is large also
 reducing the magnetosphere standoff distance.

The simulations scaling shows an underestimation of the exoplanet radio emission by
 the theoretical scaling for space weather conditions leading to a strongly compressed or van-
 ishing bow shock. Consequently, the radio telescope sensibility required to measure the ra-
 dio emission generated by terrestrial planets inside the habitable zone of M, K, G and F stars
 could be lower than expected.

The less restrictive conditions to the exoplanet habitability are linked to a radio emis-
 sion signal with rather low variability. This is the case for simulations with low SW dynamic
 pressure and IMF intensity, that is to say, space weather conditions leading to magnetopause
 standoff distances further away from the exoplanet surface.

The inference of the the magnetic field intensity and topology of exoplanets may need
 long periods of observational data if one wishes to isolate the effect of the space weather con-
 ditions on the radio emission signal. The data filtering could be particularly challenging for
 the case of exoplanets exposed to recurrent extreme space weather conditions or a dominant
 IMF pressure, leading to a large radio emission variability. On the other hand, the identifica-

tion of the magnetic field characteristics for exoplanets facing more benign space weather conditions could be less complex, because the variability of the radio emission data should be smaller.

Once the properties of the exoplanet magnetic field are identified, the analysis of the radio emission time series opens the possibility of tracking the space weather conditions on the exoplanet orbit, providing important information about the host star as the magnetic field or SW dynamic pressure.

5 Conclusions and discussion

Present study is dedicated to analyze the interaction between the stellar wind and exoplanets with an Earth-like magnetosphere hosted by M stars and F star type τ Boo, in particular the habitability restrictions induced by the sterilizing effect of the stellar wind on the exoplanet surface if the magnetosphere shielding is inefficient. The radio emission generated by exoplanets with an Earth-like magnetosphere is also calculated for different space weather conditions. With that aim, a set of MHD simulations were performed reproducing the interaction of the stellar wind with the exoplanet magnetosphere during regular and extreme space weather conditions.

The simulations results indicate that exoplanets with an Earth-like magnetosphere hosted by a M star at 0.2 au are protected from the stellar wind during regular and CME-like space weather conditions. This protection holds if the rotation period of the star is 3 days or larger, although fast rotators can constrain the exoplanet habitability due to the generation of intense and recurrent CME-like events (?). Likewise, if the exoplanet orbit is at 0.1 au, the magnetosphere protection only holds for M stars with a rotation period of 12 days or larger. On the other hand, if the exoplanet orbit is below 0.1 au, the magnetic field must be stronger regarding the Earth to avoid the direct impact of the stellar wind at low latitudes, particular during CME-like space weather conditions. It should be noted that the discussion about the properties of the terrestrial exoplanet magnetic fields, for example the type of internal magnetic dynamo at different orbits, the spinning rotation speed or the synchronicity with the host star are not explored in this study, although these effects must be consider to improve the accuracy of the predictions (?).

If the exoplanet is hosted by a F stars like τ Boo inside the habitable zone, regular space weather conditions do not impose strong constraint on the habitability. On the other hand, if the exoplanet orbit is close to the inner boundary of the habitable zone (2.5 au), an efficient shielding during CME-like space weather conditions requires a stronger magnetic field compared to the Earth. The introduction of the effect of the star rotation in the analysis indicates that the direct precipitation of the SW can occur if the star rotation period is below 10 days for exoplanets at 2.5 au during extreme space weather conditions, although for exoplanets at 5 au the star rotation period must be 2 days or lower.

The radio emission calculated in simulations with a dynamic pressure between $P_d = 2.5$ – 14 nPa shows the same order of magnitude regarding the scaling proposed by ? (?), predicting $7.5 \cdot 10^7$ W. That is to say, the radio emission obtained in the simulations is consistent with the scaling during regular and weak CME-like space weather conditions. Likewise, simulations with fixed dynamic pressure ($P_d = 1.2$ nPa) also show radio emission values comparable with ? (?) scaling if the IMF intensity is in the range of values observed during regular to strong CME-like space weather conditions. In addition, the southward IMF orientation leads to the strongest radio emission and the northward IMF to the lowest. The simulations indicate an enhancement of the radio emission as the stellar wind dynamic pressure and IMF intensity increase. Consequently, radio telescopes may receive a stronger signal from exoplanets hosted by stars with large magnetic activity and intense stellar wind (high SW density and velocity), particularly if the exoplanet orbit is close to the star. Nevertheless, such adverse space weather conditions requires an exoplanet with a intense magnetic field that avoids the collapse of the magnetopause on the exoplanet surface. Such ensemble of space weather and exoplanet

628 magnetic field characteristics are found in Hot Jupiters, reason why the first potential detec-
 629 tion of radio emission from an exoplanet involved the Hot Jupiter τ Boo b (?, ?). Unfortunately,
 630 the radio emission detection from exoplanets hosted by stars with more favorable habitabil-
 631 ity conditions regarding the space weather inside habitable zone, will require a new genera-
 632 tion of radio telescopes with improved resolution and sensibility because the radio emission
 633 signal should be several orders of magnitude smaller compared to Hot Jupiters.

634 The simulations indicate a larger variability of the exoplanet radio emission induced by
 635 the IMF orientation if the bow shock does not exist, that is to say, the stellar wind dynamic
 636 pressure is low enough and the IMF intensity high enough to be in the parametric range of
 637 $M_A < 1$. On the other hand, the radio emission variability caused by the IMF orientation is
 638 smaller if the bow shock exist ($M_A > 1$). That happens because, if the bow shock exist, there
 639 is a component of the radio emission linked to the compression and bending of the IMF lines
 640 in the nose of the bow shock, mainly dependent on the dynamic pressure of the stellar wind.
 641 Thus, the radio emission sources are the bow shock compression and the reconnection site be-
 642 tween IMF and exoplanet magnetic field. Consequently, the role of the IMF orientation is smaller
 643 with respect to the configurations without bow shock. The implication of this result is that ex-
 644 oplanet magnetospheres routinely perturbed by intense IMF avoiding the formation of the bow
 645 shock ($M_A < 1$) may show a larger radio emission variability with respect to exoplanet mag-
 646 netospheres with a bow shock. That is to say, if the exoplanet is hosted by a star with strong
 647 magnetic activity although relative low stellar wind dynamic pressure, the radio telescopes may
 648 measure a large time variability induced by changes in the IMF orientation, particularly if the
 649 magnetosphere erosion leads to a magnetopause located close to the exoplanet surface. Hence,
 650 if radio telescopes routinely measure relatively strong and very variable signal, the exoplanet
 651 habitability conditions may not be optimal from the point of view of the space weather and
 652 the exoplanet magnetic field intensity. The same way, if the host star has a relative weak mag-
 653 netic activity although generates intense stellar winds (large dynamic pressure), the radio emis-
 654 sion detected must be relatively large and show a small variability, pointing out a large com-
 655 pression of the exoplanet magnetosphere and low magnetopause standoff distances, thus the
 656 exoplanet habitability state regarding the space weather conditions and the intrinsic magnetic
 657 field is less favorable. Therefore, the combination of low radio emission and small variabil-
 658 ity may indicate the space weather conditions and the intrinsic magnetic field of the exoplanet
 659 support lower limitations for the exoplanet habitability, efficiently shield by the magnetosphere
 660 from the sterilizing effect of the stellar wind.

661 The analysis of the simulations combining the effect of the SW dynamic pressure with
 662 the IMF orientation and intensity shows radio emission values between $3 \cdot 10^7$ W for com-
 663 mon CME up to $2 \cdot 10^{10}$ W for super CME. The simulations with large SW dynamic pres-
 664 sure and IMF intensity leads to an enhancement of the radio emission because the bow shock
 665 is strongly compressed, the reconnection between the IMF and the exoplanet magnetic field
 666 is strong and the magnetopause is located close to the exoplanet surface. The statistical anal-
 667 ysis shows similar radio emission trends with respect to the SW dynamic pressure and IMF
 668 intensity, although the scaling is slightly affected by the IMF orientation. In particular, the south-
 669 ward IMF leads to the largest IMF intensity dependency, 20% larger with respect to the SW
 670 dynamic pressure trend.

Statistical analysis of the radio emission calculated in the simulations leads to data re-
 gression exponents that deviate with respect to the radio-magnetic scaling laws (?, ?, ?). Nev-
 ertheless, the agreement improves comparing the radio-magnetic scaling law of a configura-
 tion with dominant IMF pressure and the data regression for a Southward IMF orientation. Con-
 sequently, the trends of radio-magnetic scaling law and simulations are similar if the bow shock
 does not exist and the IMF is perpendicular to the SW velocity. That means the radio-magnetic
 scaling laws does not fully capture the effect of the bow shock compression and magnetosphere
 distortion on the radio emission generation due to the combined effect of the SW and IMF.
 The scaling law obtained from the simulation is, including the range of exponent values cal-

culated for different IMF orientations:

$$P_w \propto |B|_{IMF}^{(0.9-1.22)} P_d^{(0.95-1.15)}$$

671 that is to say, the radio-magnetic scaling law for space weather conditions with a dominant
 672 SW pressure could overestimate the trend of the IMF intensity ($P_w \propto |B_{IMF,\perp}|^2$) and under-
 673 estimate the trend of the SW dynamic pressure ($P_w \propto P_d^{0.17}$). On the other hand, the predic-
 674 tion of the radio-magnetic scaling law for space weather conditions with a dominant IMF pres-
 675 sure is closer to the simulations scaling regarding the IMF intensity ($P_w \propto |B_{IMF,\perp}|^{1.3}$) and
 676 the SW dynamic pressure $P_w \propto P_d^{0.5}$). In summary, the theoretical scaling may underestimate
 677 the radio emission generation, particularly with respect to the SW dynamic pressure trend.

678 A further refinement of the simulations scaling requires an improved description of the
 679 model's physics, for example introducing the exoplanet rotation and kinetic effects. Neverthe-
 680 less, the present study provides a first order approximation of the exoplanet standoff distance
 681 and magnetospheric radio emission with respect to the space weather conditions generated by
 682 host star.

683 Appendix A Numerical model validation

684 The numerical model used in this study was also applied in the analysis of the interac-
 685 tion between the solar wind and the Earth magnetosphere (Liu et al., 2021). Part of Liu et al. (2021) study was ded-
 686 icated to analyze the perturbation induced in the magnetosphere by several CMEs that impacted
 687 the Earth from 1997 to 2020. The simulations results were compared with observational data
 688 to validate the numerical model, in particular the K_p index. The K_p index provides the global
 689 geomagnetic activity taking values from 0 if the geomagnetic activity is weak to 9 if the geo-
 690 magnetic activity is extreme (Liu et al., 2021). The K_p index was calculated in the simulations as the
 691 lowest latitude with open magnetic field lines in the Earth surface at the North Hemisphere.
 692 Figure A1 shows the correlation between the K_p index obtained in the simulations with re-
 693 spect to the measured values. The statistical analysis finds a correlation coefficient of 0.83, that
 694 is to say, a reasonable agreement between simulations and observational data. Consequently,
 695 the numerical model is valid to reproduce the global structures of the Earth magnetosphere
 696 during extreme space weather conditions, also suitable to analyze the interaction of the stel-
 697 lar wind with exoplanet magnetospheres if the intrinsic magnetic field is similar to the Earth.

698 Appendix B Calculation of the magnetopause standoff distance

The theoretical approximation of the magnetopause standoff distance is calculated as the
 balance between the dynamic pressure of the SW ($P_d = m_p n_{sw} v_{sw}^2 / 2$), the thermal pressure
 of the SW ($P_{th,sw} = m_p n_{sw} v_{th,sw}^2 / 2 = m_p n_{sw} c_{sw}^2 / \gamma$), and the magnetic pressure of the IMF
 ($P_{mag,sw} = B_{sw}^2 / (2\mu_0)$) with respect to the magnetic pressure of a dipolar magnetic field ($P_{mag,ex} =$
 $\alpha \mu_0 M_{ex}^2 / 8\pi^2 r^6$) and the thermal pressure of the magnetosphere ($P_{th,MSP} = m_p n_{MSP} v_{th,MSP}^2 / 2$).
 This results in the expression:

$$P_d + P_{mag,sw} + P_{th,sw} = P_{mag,ex} + P_{th,MSP} \quad (B1)$$

$$\frac{R_{mp}}{R_{ex}} = \left[\frac{\alpha \mu_0 M_{ex}^2}{4\pi^2 \left(m_p n_{sw} v_{sw}^2 + \frac{B_{sw}^2}{\mu_0} + \frac{2m_p n_{sw} c_{sw}^2}{\gamma} - m_p n_{MSP} v_{th,MSP}^2 \right)} \right]^{(1/6)} \quad (B2)$$

699 with M_{ex} the exoplanet dipole magnetic field moment, $r = R_{mp} / R_{ex}$, and α the dipole com-
 700 pression coefficient ($\alpha \approx 2$ (Liu et al., 2021)). This approximation does not include the effect of the re-
 701 connections between the IMF with the exoplanet magnetic fields, thus the expression assumes
 702 a compressed dipolar magnetic field, ignoring the orientation of the IMF. Here, the approx-
 703 imation is only valid if the IMF intensity is rather low and the magnetopause standoff distance
 704 should be calculated using simulations for extreme space weather conditions.

The magnetopause standoff distance is defined in the simulations analysis as the last close magnetic field line on the exoplanet dayside at 0° longitude in the ecliptic plane.

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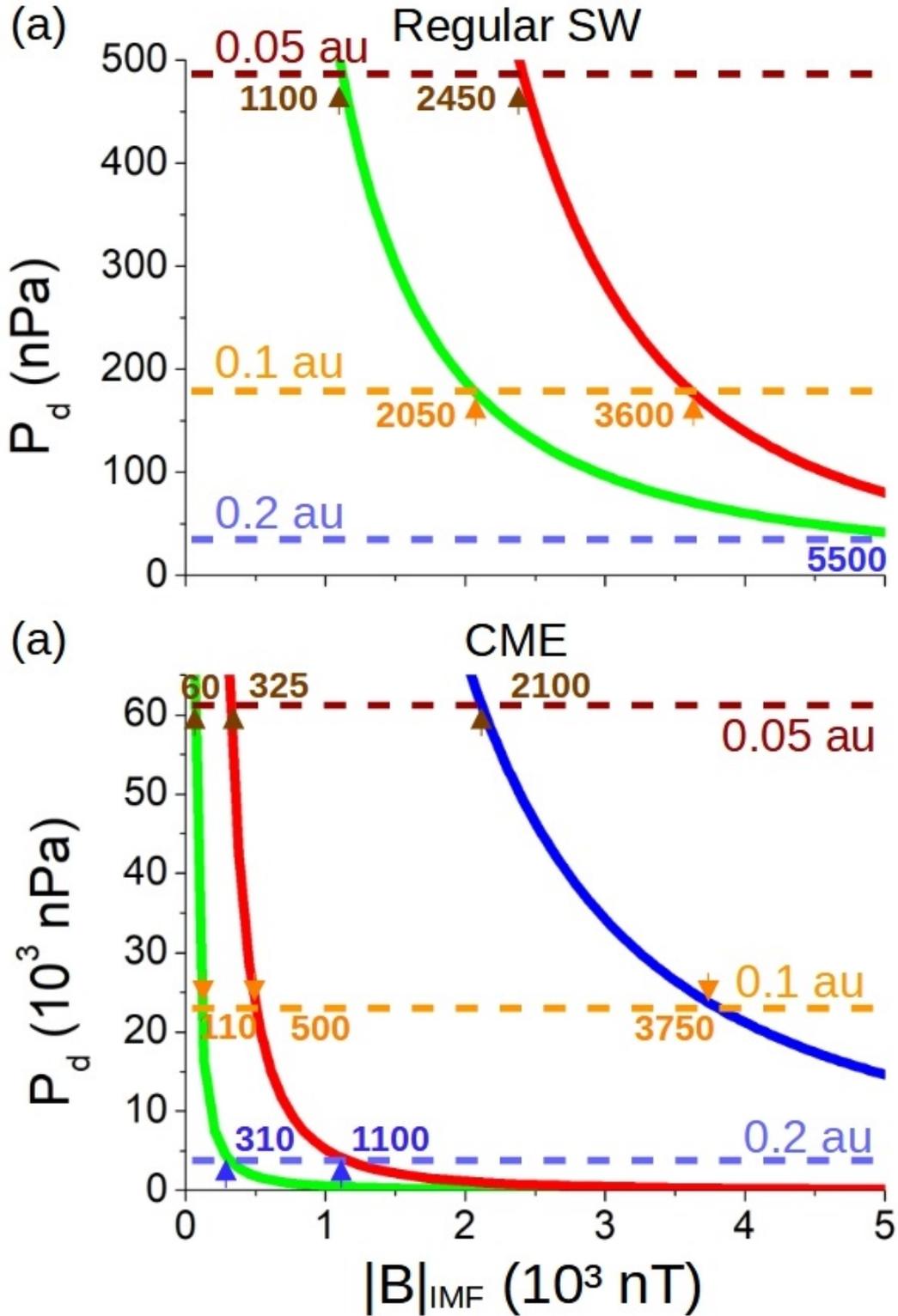
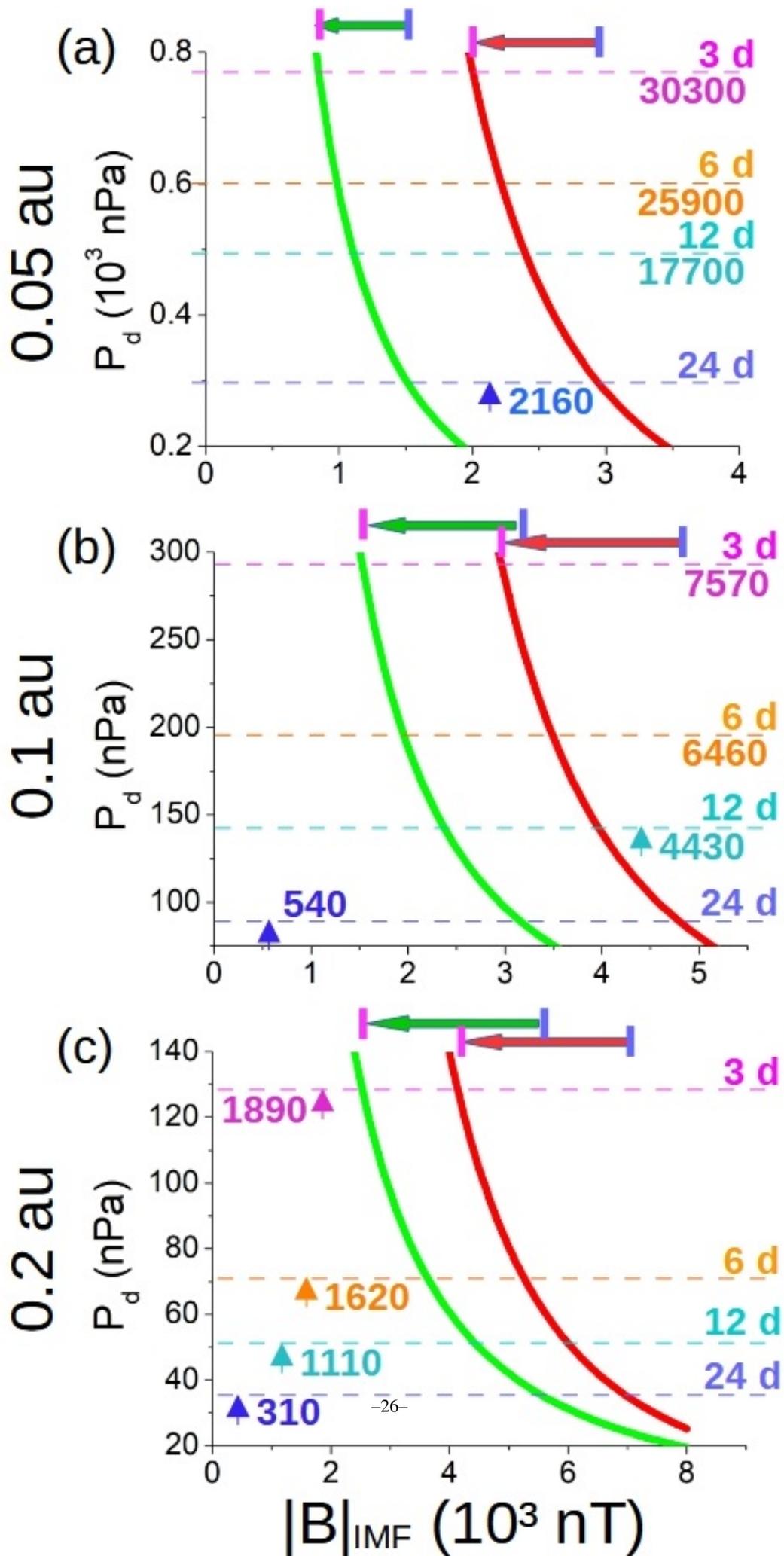


Figure 1. Critical IMF intensity and SW dynamic pressure required for the direct precipitation of the SW towards the exoplanet surface for (a) regular and (b) CME-like space weather conditions. IMF orientation: Exoplanet-star (red line), southward (green line) and northward (blue line). The horizontal dashed lines indicate the SW dynamic pressure at different exoplanet orbits: 0.05 au (red), 0.1 au (orange) and 0.2 au (blue). The critical IMF intensity is indicated for each IMF orientation.



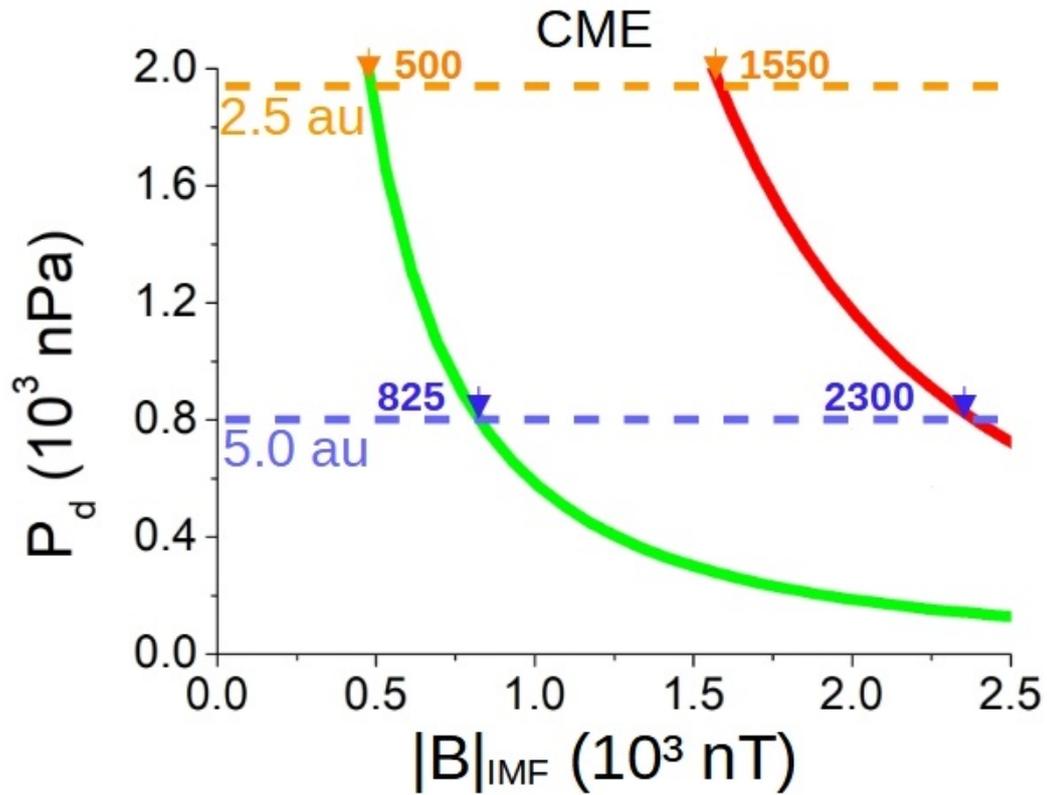


Figure 3. Critical IMF intensity and SW dynamic pressure required for the direct precipitation of the SW towards the exoplanet surface during CME-like space weather conditions. IMF orientation: Exoplanet-star (red line) and southward (green line). The horizontal dashed lines indicate the SW dynamic pressure at different exoplanet orbits: 2.5 au (orange) and 5.0 au (blue). The critical IMF intensity is indicated for each IMF orientation.

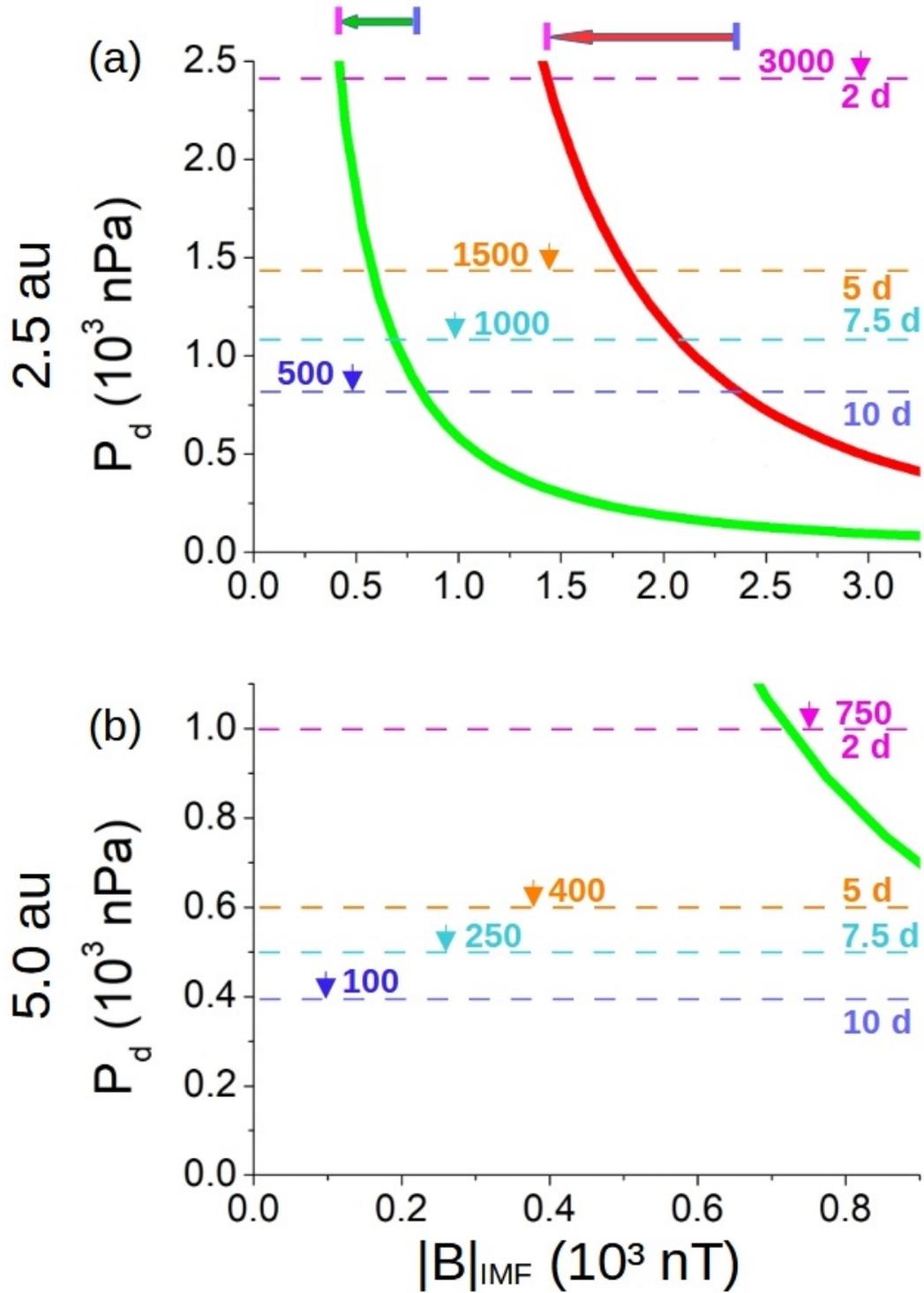


Figure 4. Critical IMF intensity and dynamic pressure required for the direct precipitation of the SW considering different F star rotation periods and exoplanets located at 2.5 au (a) and 5.0 au (b) orbits. IMF orientation: Exoplanet-star (red line) and southward (green line). The horizontal dashed lines indicate the SW dynamic pressure for F stars with rotation periods: 10 days (blue), 7.5 days (light cyan), 5 days (orange) and 2 days (pink). The bold colored arrows show the decrease of the critical IMF intensity required for the direct SW deposition if the F star rotation increases from 10 to 2 days. The green (red) color of the bold arrow indicates a southward (exoplanet-star) IMF orientation. The tentative critical IMF intensity is indicated for each star rotation rate.

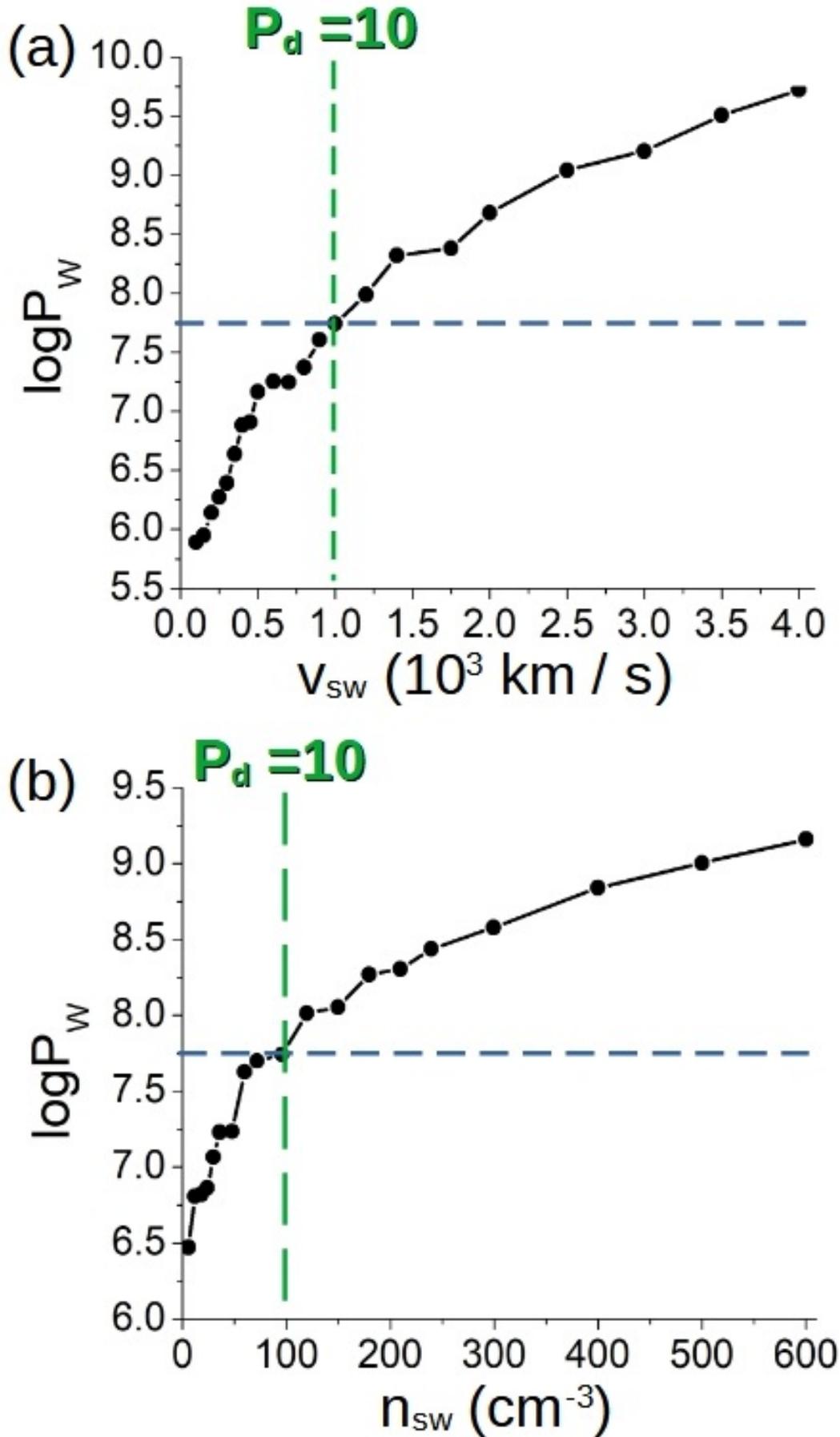


Figure 5. Radio emission power generated in the ²⁹day side of the exoplanet magnetosphere for a star-exoplanet IMF orientation with $|B|_{IMF} = 10$ nT if (a) the SW density is fixed to 12 cm^{-3} and the SW velocity changes and (b) the SW velocity fixed to 350 km/s and the SW density changes. The blue dashed horizontal line indicate the radio emission derived from the scaling law by ? (?). The green dashed vertical line indicates the simulations with $P_d = 10$ nPa.

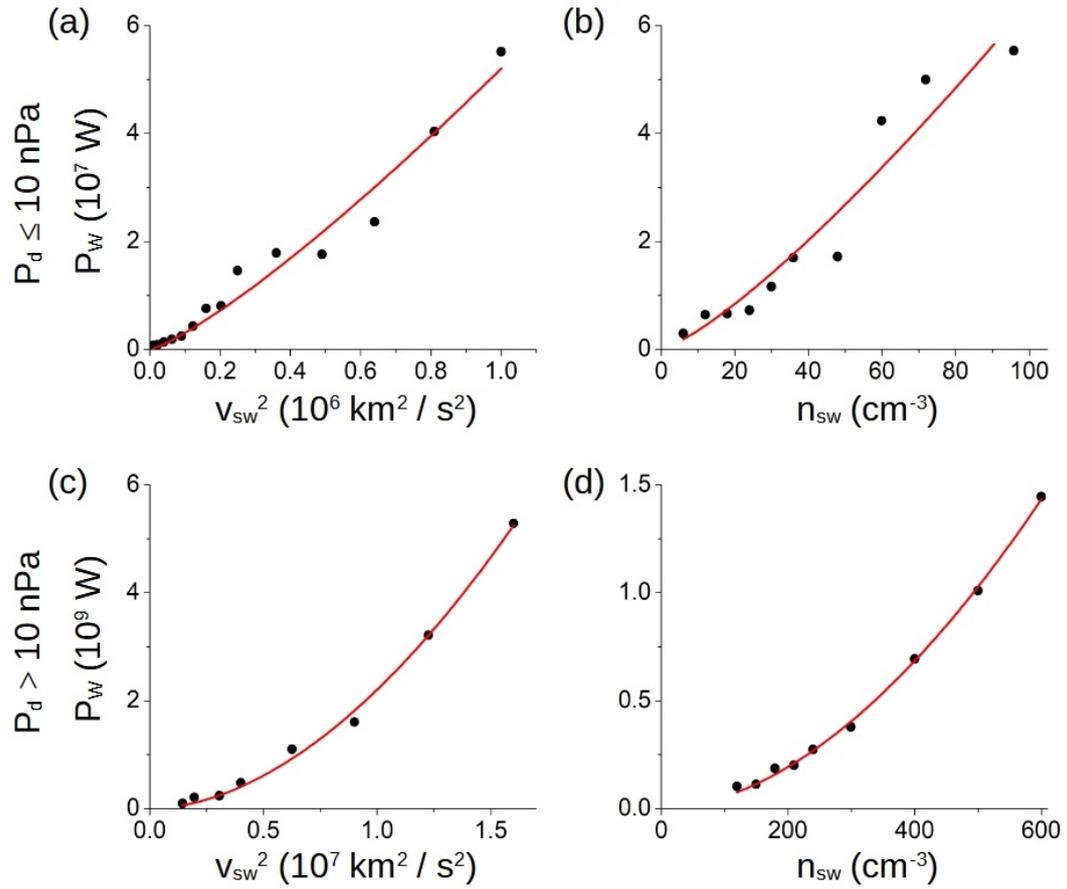


Figure 6. Data regression of the radio emission with respect to the square value of the SW velocity for (a) $P_d \leq 10$ and (c) $P_d > 10$. Data regression of the radio emission with respect to the SW density for (b) $P_d \leq 10$ and (d) $P_d > 10$.

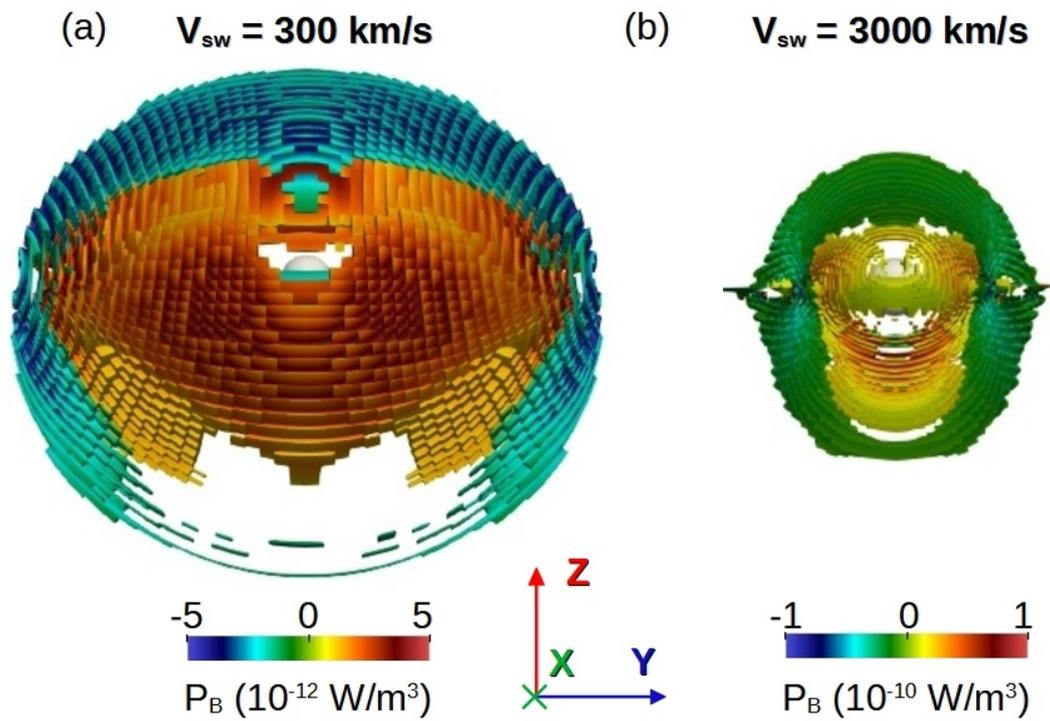


Figure 7. Iso-volume of the Poynting flux divergence in the bow shock and magnetopause region for simulations with (a) $v_{sw} = 300 \text{ km/s}$ and (b) $v_{sw} = 3000 \text{ km/s}$. Star-exoplanet IMF orientation with $|B|_{IMF} = 10 \text{ nT}$ and SW density of 12 cm^{-3} . Both panels show plots with the same dimensional scale.

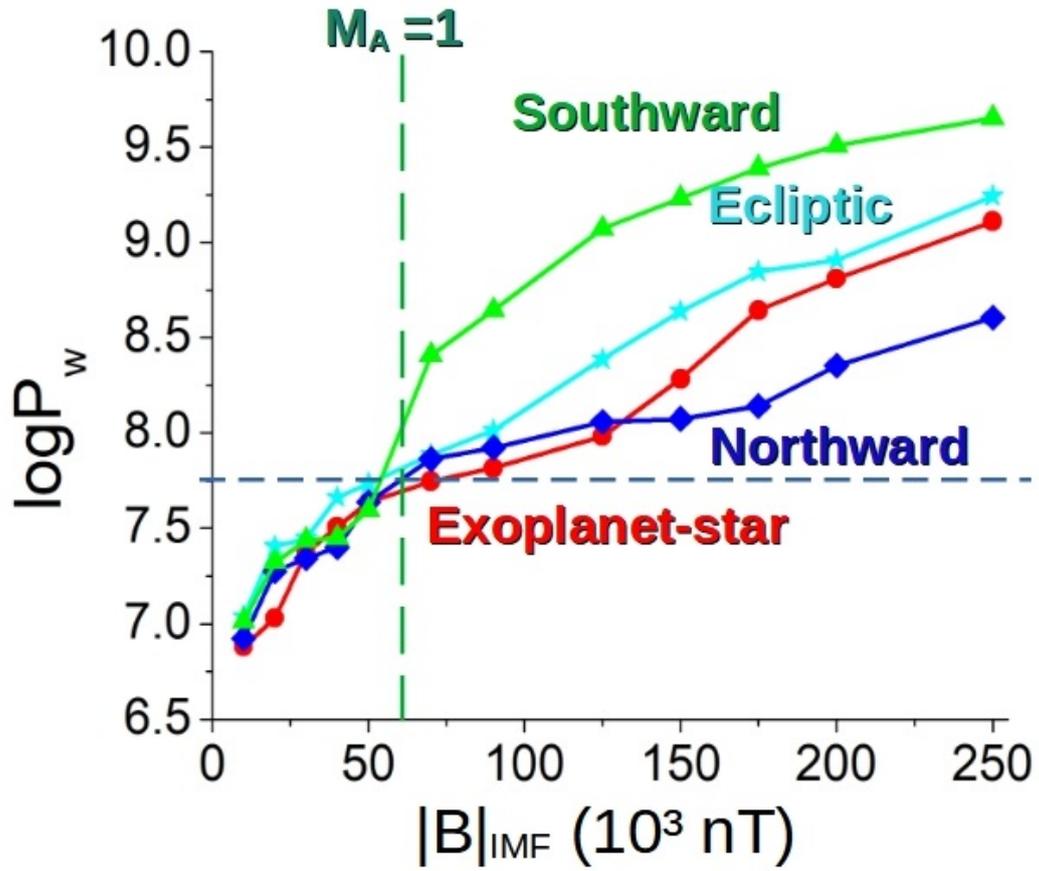


Figure 8. Logarithm of the radio emission power for simulations with $P_d = 1.2$ nPa and $|B|_{IMF} = 10 - 250$ nT. IMF orientations: Exoplanet-star (red dots), northward (blue diamonds), southward (green triangle) and ecliptic (cyan stars). The blue dashed horizontal line indicate the radio emission range derived from the scaling law by (?), (?). The dark green dashed vertical line indicates the simulations with $M_A < 1$ (right) and $M_A > 1$ (left).

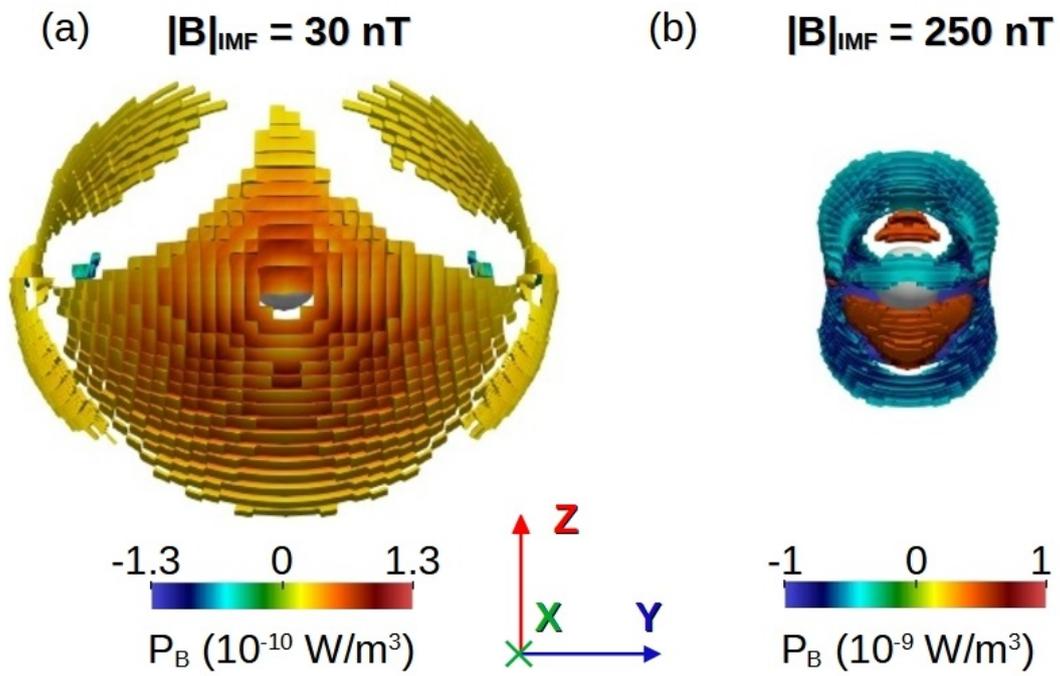


Figure 9. Iso-volume of the Poynting flux divergence in the bow shock and magnetopause region for simulations with (a) $|B|_{IMF} = 30 \text{ nT}$ and (b) $|B|_{IMF} = 250 \text{ nT}$. Exoplanet-star IMF orientation and $P_d = 1.2 \text{ nPa}$. Both panels show plots with the same dimensional scale.

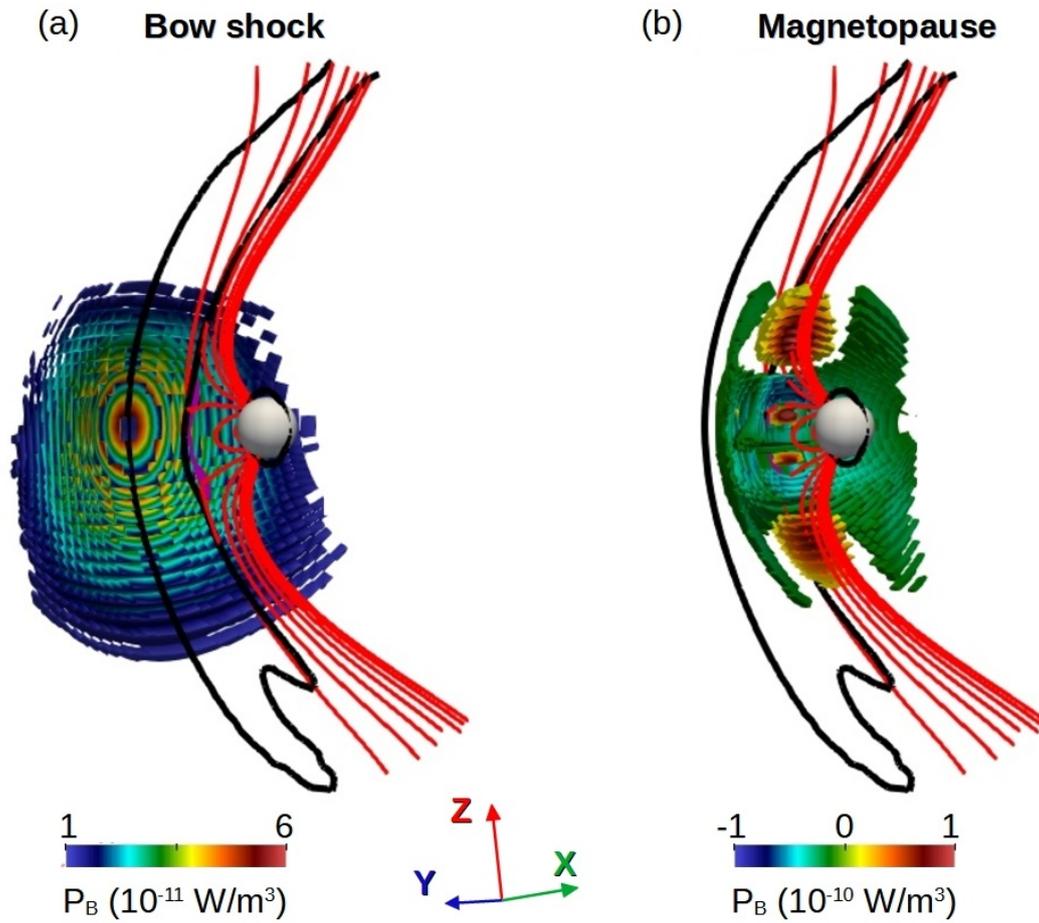


Figure 10. Poynting flux divergence in (a) the bow shock nose and (b) magnetopause reconnection regions. Simulation with southward IMF orientation, $|B|_{IMF} = 30 \text{ nT}$ and $P_d = 1.2 \text{ nPa}$. Black lines indicate the region of the bow shock ($n > 20 \text{ cm}^{-3}$), the red lines the exoplanet magnetic field lines and the pink iso-surface the reconnection region in the XZ plane ($|B| < 5 \text{ nT}$).

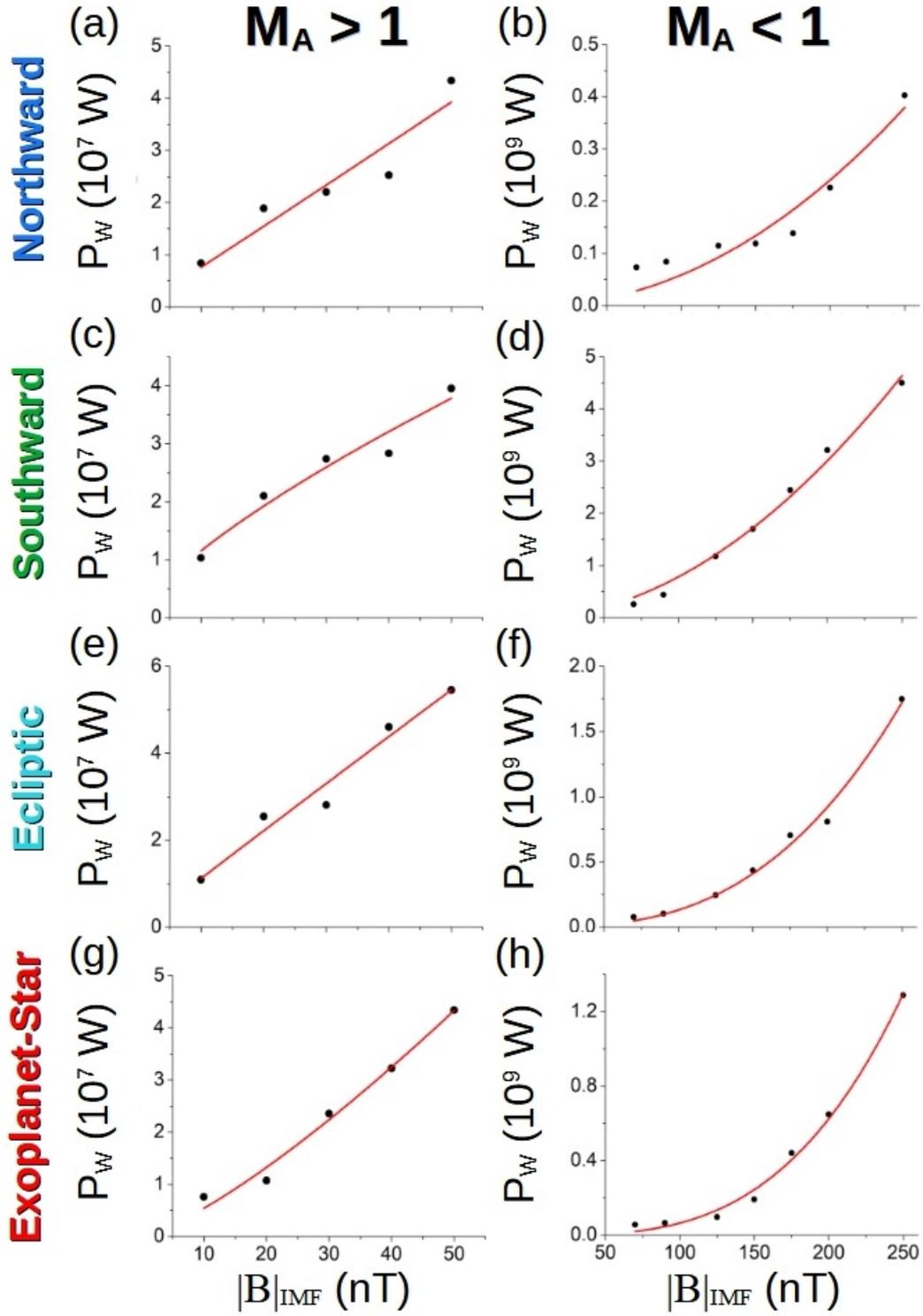


Figure 11. Data fit of the regression $P_w \approx \Gamma|B|_{sw}^\alpha$ if $|B|_{sw} < 70$ for (a) northward, (c) southward, (e) ecliptic and (g) exoplanet-star IMF. Same data regression if $|B|_{sw} \geq 70$ for (b) northward, (d) southward, (f) ecliptic and (h) exoplanet-star IMF.

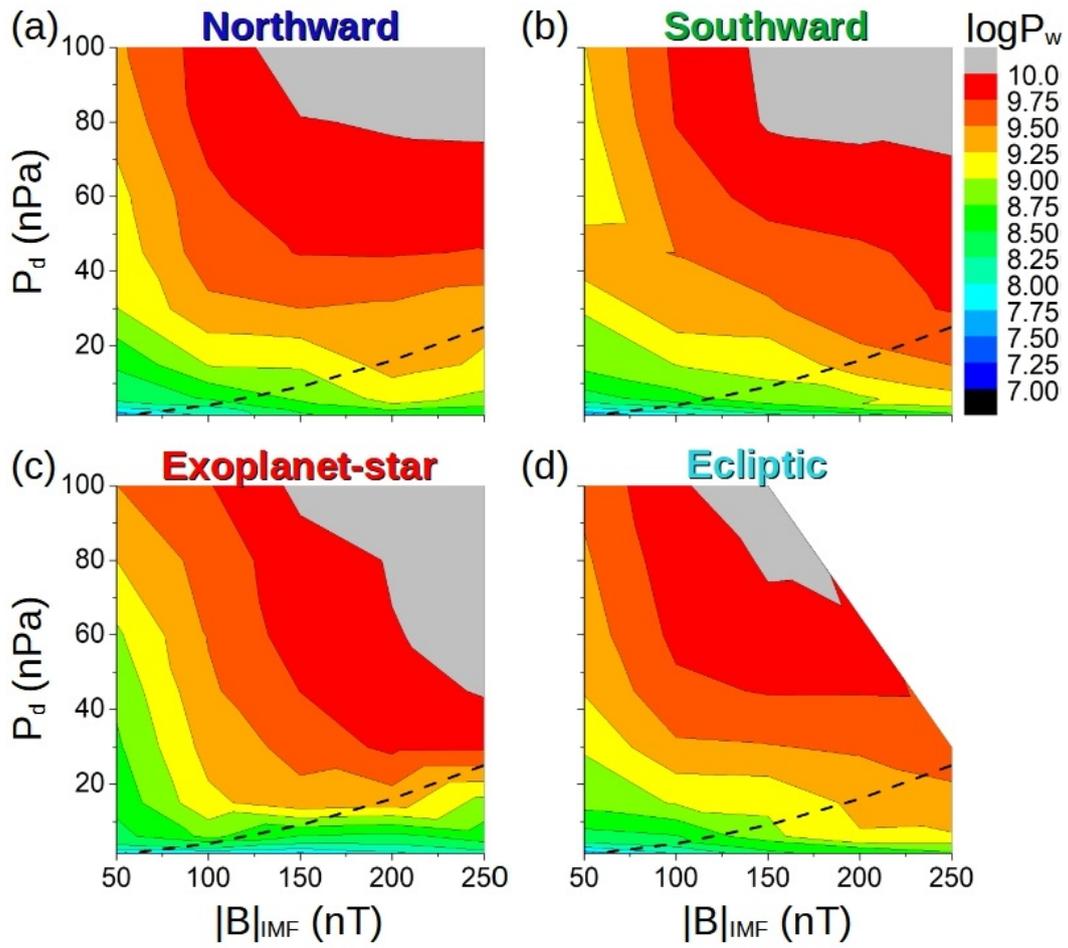


Figure 12. Logarithm of the radio emission with respect to the SW dynamic pressure and IMF intensity for (a) northward, (b) southward, (c) exoplanet-star and (d) ecliptic orientation. The dashed black line indicates the simulations with dominant SW pressure (above the line) and dominant IMF pressure (below the line).

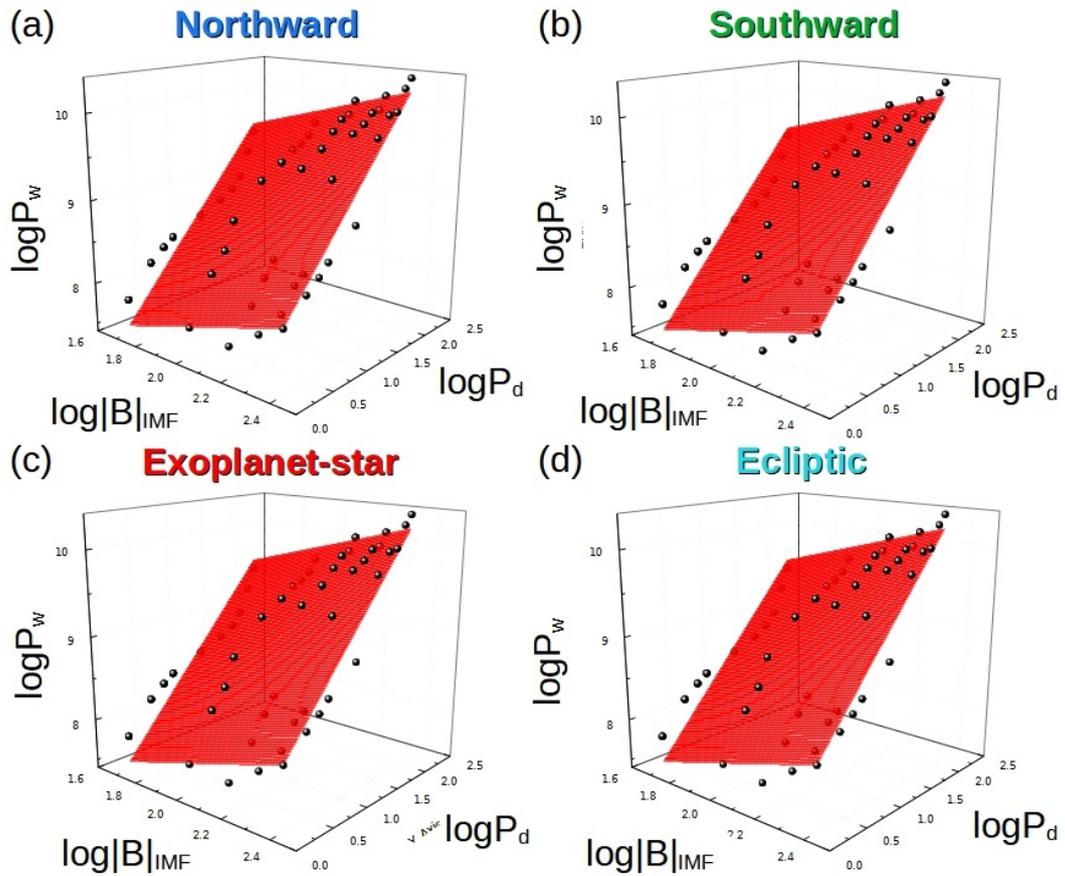


Figure 13. Data fit of the regression $\log P_w \propto \log Z + M \log(|B|_{IMF}) + N \log(P_d)$ for (a) northward, (b) southward, (c) exoplanet-star and (d) ecliptic IMF.

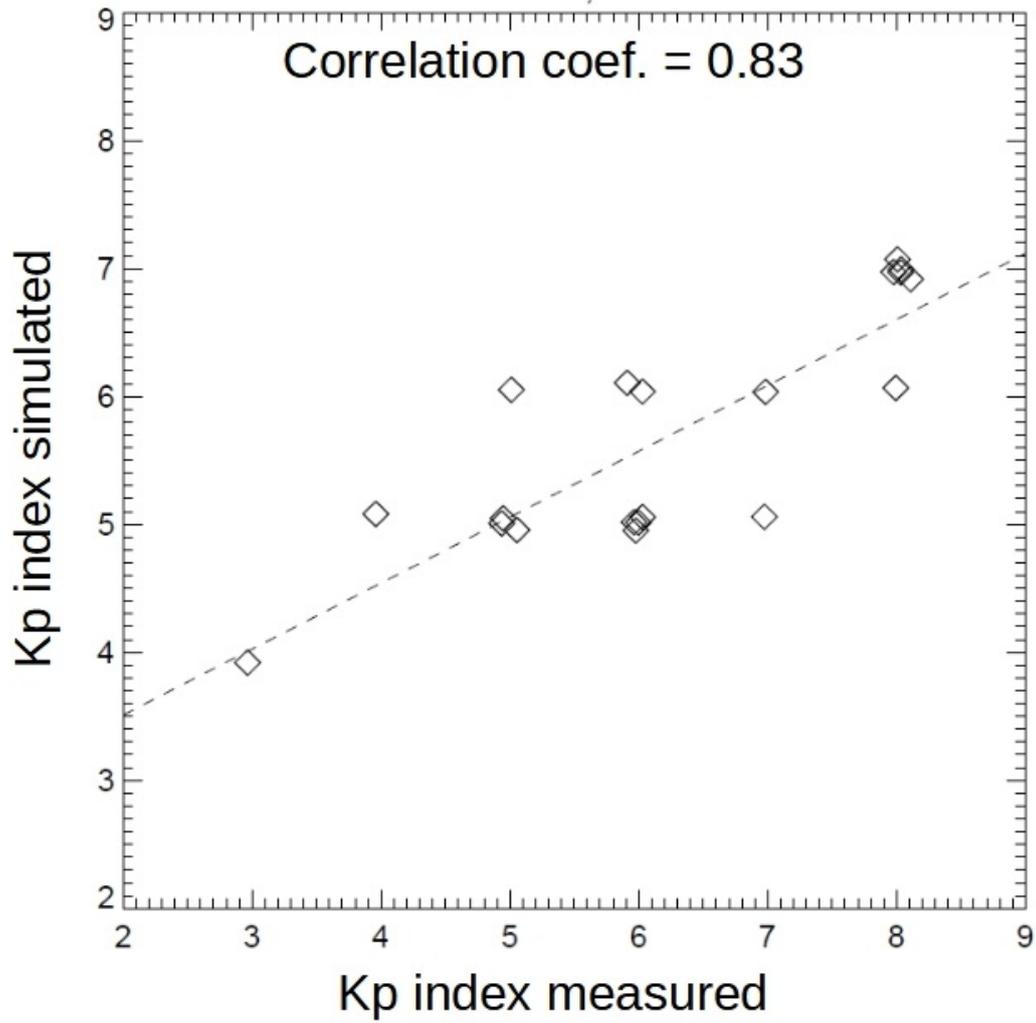


Figure A1. Correlation between the K_p index obtained in the simulations with respect to the measured values.