Stellar Wind Impact On The Evolution Of Early Atmospheres Around Terrestrial Planets

A MHD Approximation

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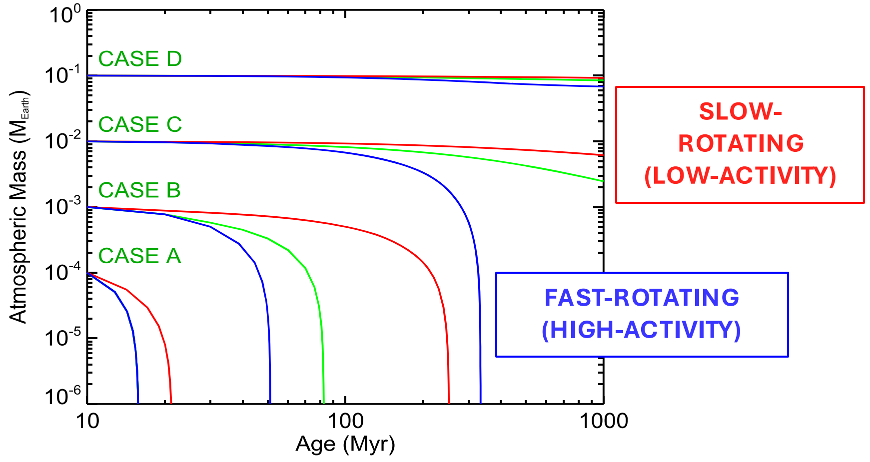
NUVA eMeeting 2024
The impact of UV surveys in astronomy

Planet-star interactions: The role of stellar winds

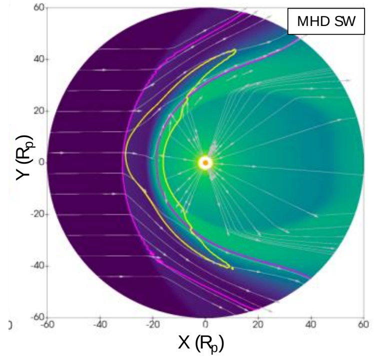
- **XUV radiation (<912 Å)** controls the evolution of the first atmospheres around Earth-like exoplanets.

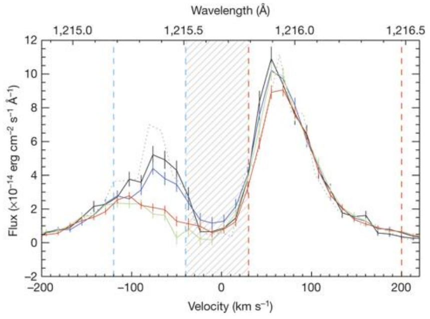
1D HD simulations; $1M_{\oplus}$ at 1 AU



Johnstone et al. (2015)

- **Stellar winds** play also a fundamental role on atmospheric evolution, shaping the **morphology** of the remanent atmospheres **(detection)** and driving additional **atmospheric losses (survival).**





Stellar wind impact on early atmospheres around unmagnetized Earth-like planets

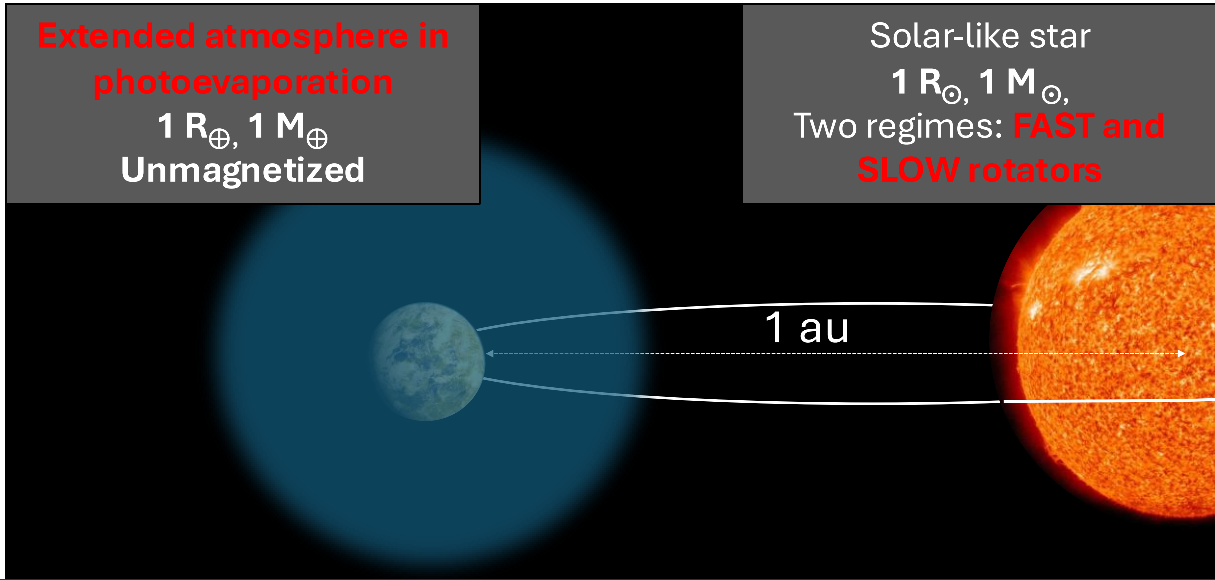
AIMS OF THIS WORK

1) Study the **contribution of stellar winds** to the **evolution of the primordial atmospheres** in photoevaporation around terrestrial planets (**50 – 500 Myr**).

2) Evaluate influence of stellar winds from **both fast- and slow-rotating stars.**

3) Evaluate possible **emission in UV tracers (T~10^4-10^5 K)** from plasma interaction. Detection with future infrastructures (**HWO).**

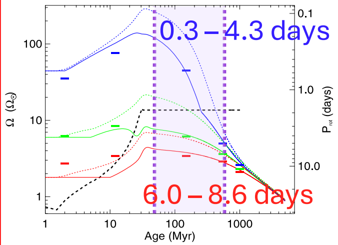
- **3D MHD simulations**
- **Canet, Varela & Gómez de Castro (2024) - MNRAS**



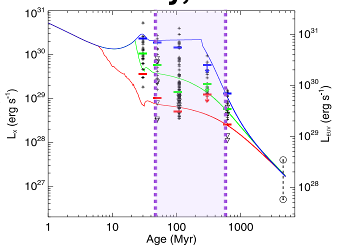
Stellar wind evolution: fast- and slow-rotating stars

Evolutional models for SW 'ingredients'

Rotation

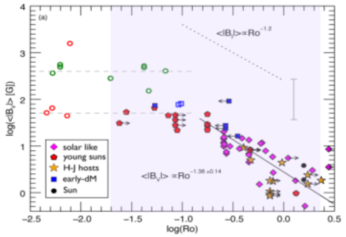


X-ray, EUV



Tu et al. (2015)

Surface magnetic field



Vidotto et al. (2014)

+

Weber & Davis model for the stellar wind structure

$$V_r \frac{dV_r}{dr} = -\frac{1}{\rho}\frac{dp}{dr} - \frac{GM_\star}{r^2} + \frac{V_\phi^2}{r} - \frac{B_\phi}{4\pi\rho r}\frac{d}{dr}(rB_\phi)$$

Pressure gradient — Stellar gravity — Centrifugal acceleration — Rotational magnetic field

Super-fast magnetosonic
Super-Alfvénic

SHOCKS EXPECTED!

Stellar wind parameters: Fast rotator

model	Age (Myr)	v_r (km/s)	v_ϕ (km/s)	n_p (cm^{-3})	B_r (mG)	B_ϕ (mG)	T (MK)	M_A	M_f	p_{ram} (dyn cm^{-2})	SAT
F1	50	2629	67	66	0.418	6.91	4.1	1.4	1.4	7.6×10^{-6}	yes
F2	150	1948	35	51	0.418	3.33	4.1	1.8	1.8	3.2×10^{-6}	yes
F3	300	1525	10	38	0.331	0.94	3.7	4.2	3.5	1.5×10^{-6}	no
F4	500	1175	3	24	0.121	0.26	2.2	9.0	5.1	5.5×10^{-7}	no

Stellar wind parameters: Slow rotator

model	Age (Myr)	v_r (km/s)	v_ϕ (km/s)	n_p (cm^{-3})	B_r (mG)	B_ϕ (mG)	T (MK)	M_A	M_f	p_{ram} (dyn cm^{-2})	SAT
S1	50	1005	1.7	20	0.075	0.134	1.7	13.4	5.5	3.4×10^{-7}	no
S2	150	969	1.5	17	0.065	0.107	1.6	14.3	5.5	2.6×10^{-7}	no
S3	300	929	1.4	31	0.058	0.092	1.5	15.3	5.6	2.2×10^{-7}	no
S4	500	804	1.4	29	0.054	0.085	1.1	13.9	5.5	1.6×10^{-7}	no

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Modelization

PLUTO MHD ideal module

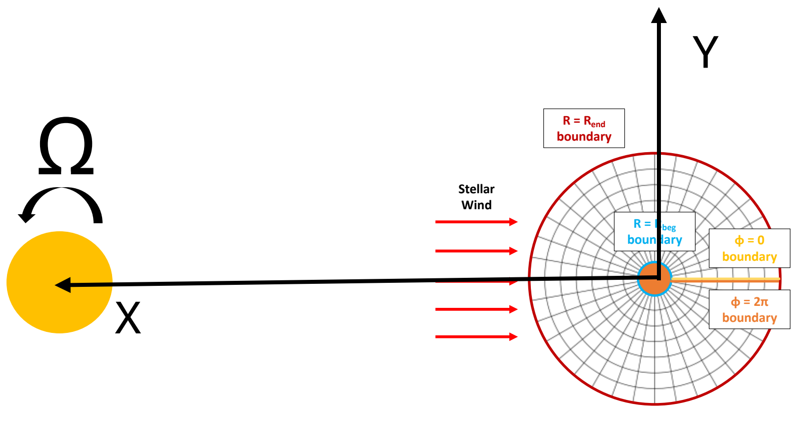
3D, Spherical coordinates

$r \in [2.5, 60 R_p]$ 732 points

$\theta \in [0, \pi]$ 96 points

$\phi \in [0, 2\pi]$ 192 points

(RESOLUTION: 0.08 – 1.9 R_p)



θ = π/2 plane
XY plane (ecliptic)

$$\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{v}) = 0$$

$$\frac{\partial (\rho \mathbf{v})}{\partial t} + \nabla \cdot \left[\rho \mathbf{v}\mathbf{v} - \frac{\mathbf{B}\mathbf{B}}{4\pi} + p_T \mathbf{I} \right]^T = \rho (\mathbf{g} + \mathbf{F}_{Cor} + \mathbf{F}_{cen})$$

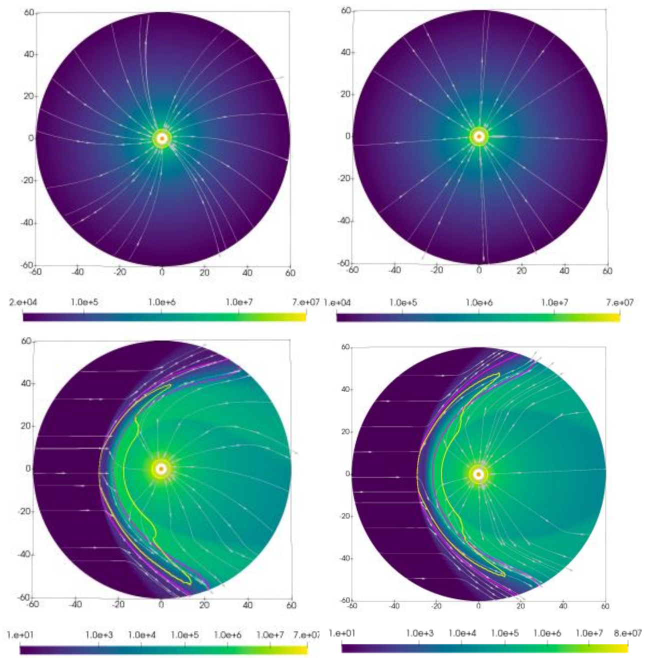
$$\frac{\partial E_T}{\partial t} + \nabla \cdot \left[(E_T + p_T)\mathbf{v} - \frac{\mathbf{B}}{4\pi}(\mathbf{v} \cdot \mathbf{B}) \right] = \rho \left(\mathbf{g} + \mathbf{F}_{cen} \right) \cdot \mathbf{v}$$

$$\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{B} \times \mathbf{v}) = 0$$

$$\rho \epsilon = \frac{p}{\gamma - 1} \qquad \gamma = 1.01 \qquad \text{Quasi-isothermal}$$

$$\mathbf{F}_{Cor} = -2(\mathbf{\Omega} \times \mathbf{v})$$

$$\mathbf{F}_{cen} = -\mathbf{\Omega} \times (\mathbf{\Omega} \times \mathbf{v})$$



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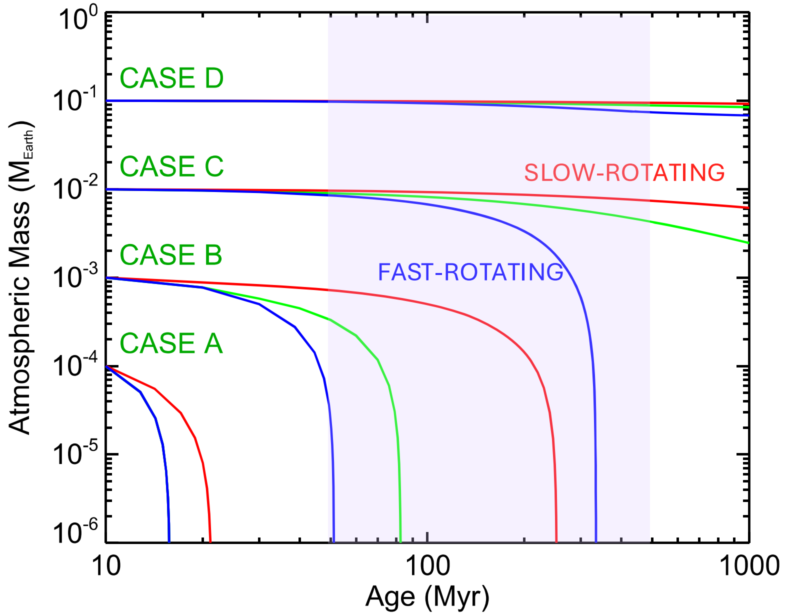
Modelization: Photoevaporating atmospheres

1D HD models of the evolution of planetary atmospheres under the influence of XUV radiation

Case C in Johnstone et al. (2015, **initial f_{atm} = 0.01M_p**)

$$\dot{M}_{atm} = 1.858 \times 10^{31} m_H z_0^{0.464} (log F_{XUV})^{4.093 z_0^{-0.022}}$$

$$z_0 = R_0 - R_{core} \qquad log\left(\frac{R_0}{R_{core}}\right) = (2.5 f_{atm}^{0.4} + 0.1)\left(\frac{M_p}{M_\oplus}\right)^{-0.7}$$



Atmospheric parameters: Fast rotator

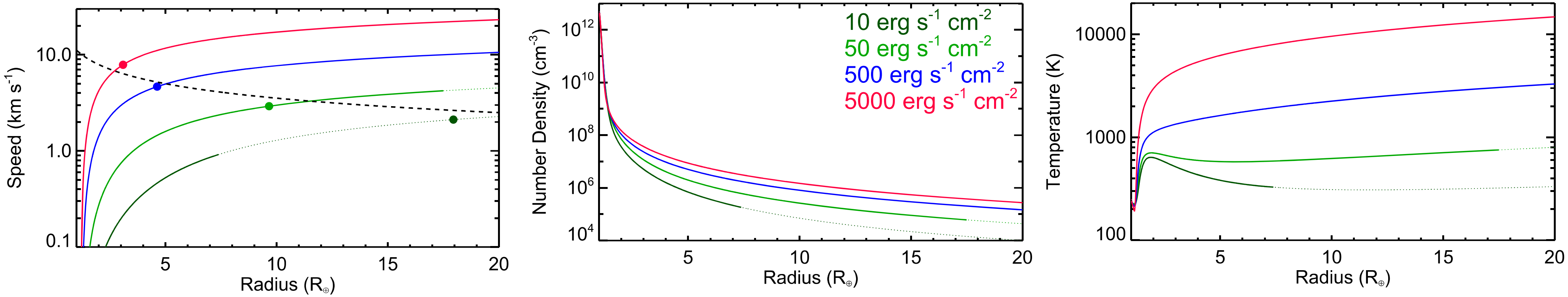
model	Age (Myr)	F_{XUV} (erg s^{-1} cm^{-2})	f_{atm}	R_0 (R_p)	$\dot{M}$ (1×10^9 g/s)	T (K)	n_0 (cm^{-3})
F1	50	3443	1×10^{-2}	2.4	6.1	5000	6.5×10^8
F2	150	3443	5×10^{-3}	2.0	5.5	5000	6.0×10^8
F3	300	2268	1×10^{-3}	1.7	3.9	4000	4.7×10^8
F3b	300	2268	1×10^{-6}	1.7	1.9	4000	2.0×10^8
F4	500	542	-	-	-	2000	1.0×10^6

Atmospheric parameters: Slow rotator

model	Age (Myr)	F_{XUV}	f_{atm}	R_0 (R_p)	$\dot{M}$ (1×10^9 g/s)	T (K)	n_0 (cm^{-3})
S1	50	224	1×10^{-2}	2.4	1.2	1200	2.6×10^8
S2	150	182	1×10^{-2}	2.4	1.0	1100	2.5×10^8
S3	300	132	8×10^{-3}	2.3	0.8	1000	2.1×10^8
S4	500	95	7×10^{-3}	2.2	0.5	900	1.5×10^8

Modelization: Photoevaporating atmospheres

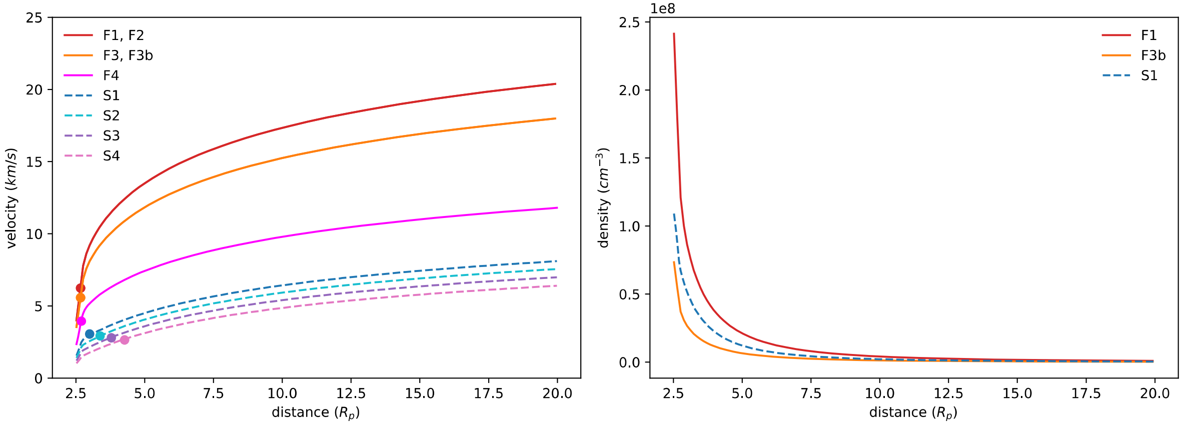
Johnstone et al. (2015, 1D HD models, **heating by XUV radiation)**



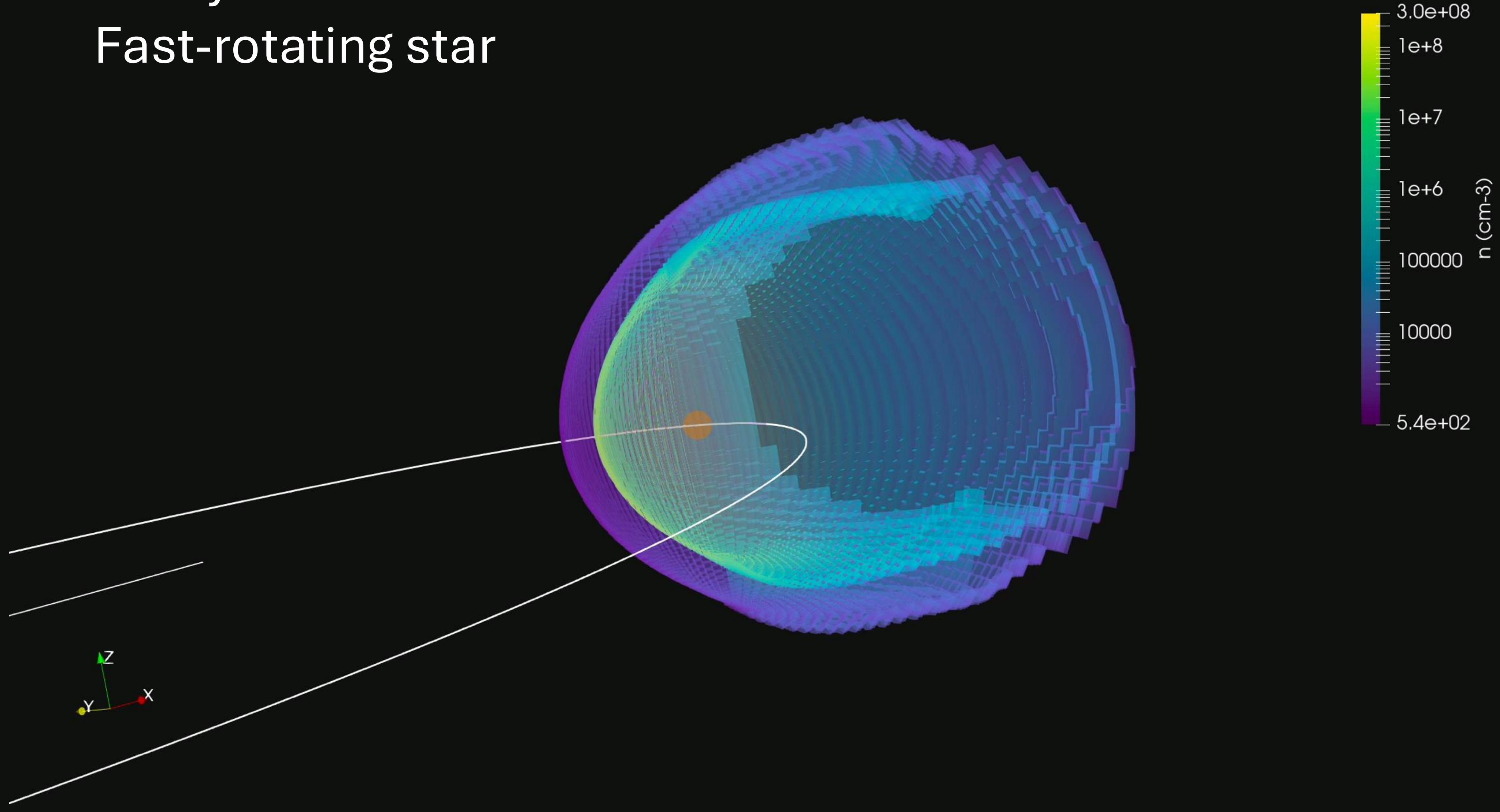
PLUTO MHD

model	Age (Myr)	F_{XUV} (erg s^{-1} cm^{-2})	T (K)	n_0 (cm^{-3})
F1	50	3443	5000	6.5×10^8
F2	150	3443	5000	6.0×10^8
F3	300	2268	4000	4.7×10^8
F3b	300	2268	4000	2.0×10^8
F4	500	542	2000	1.0×10^6

model	Age (Myr)	F_{XUV}	T (K)	n_0 (cm^{-3})
S1	50	224	1200	2.6×10^8
S2	150	182	1100	2.5×10^8
S3	300	132	1000	2.1×10^8
S4	500	95	900	1.5×10^8

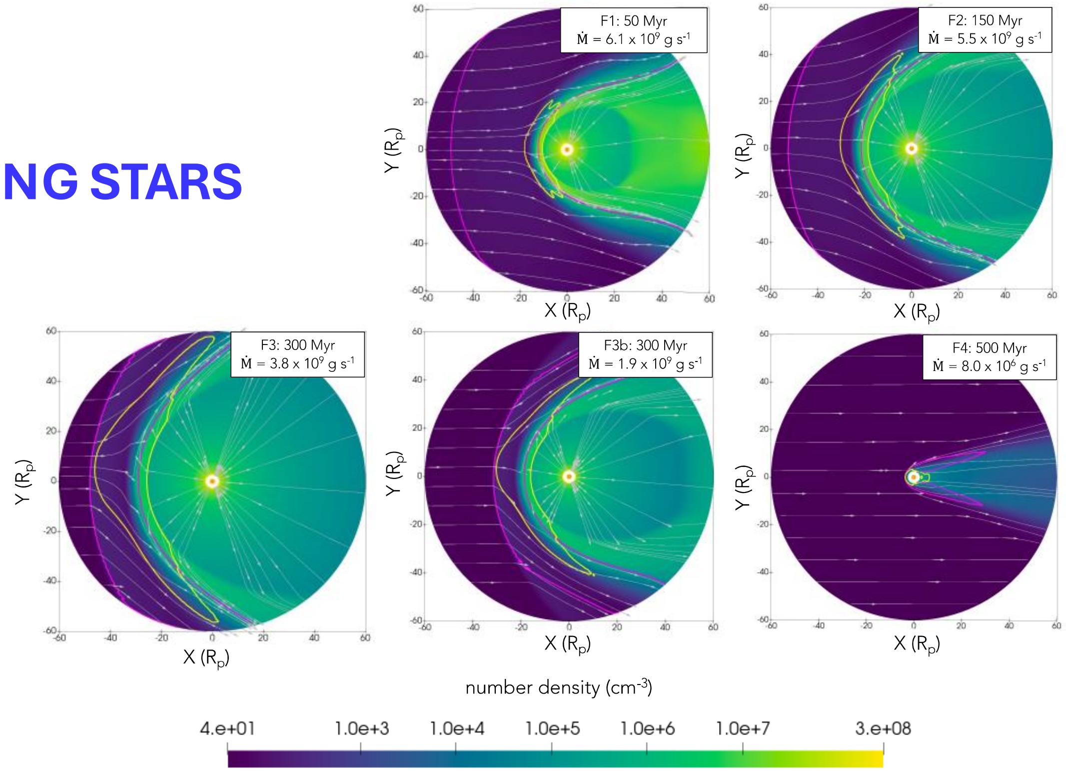


50 Myr
Fast-rotating star

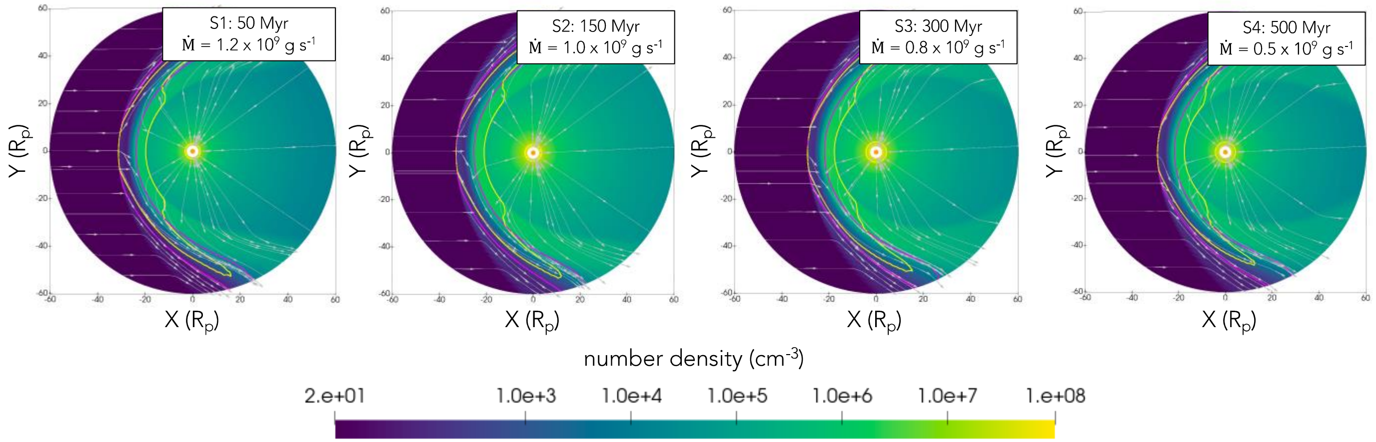


Results

FAST-ROTATING STARS



SLOW-ROTATING STARS



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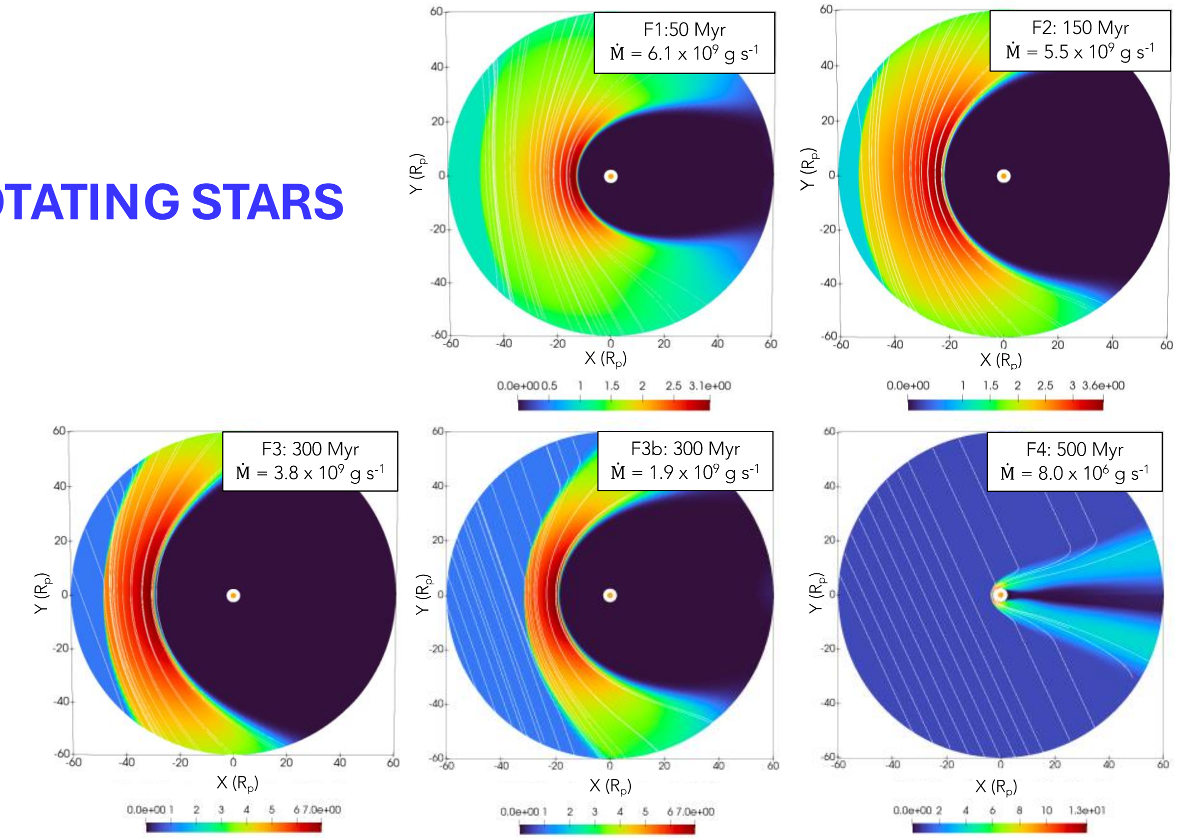
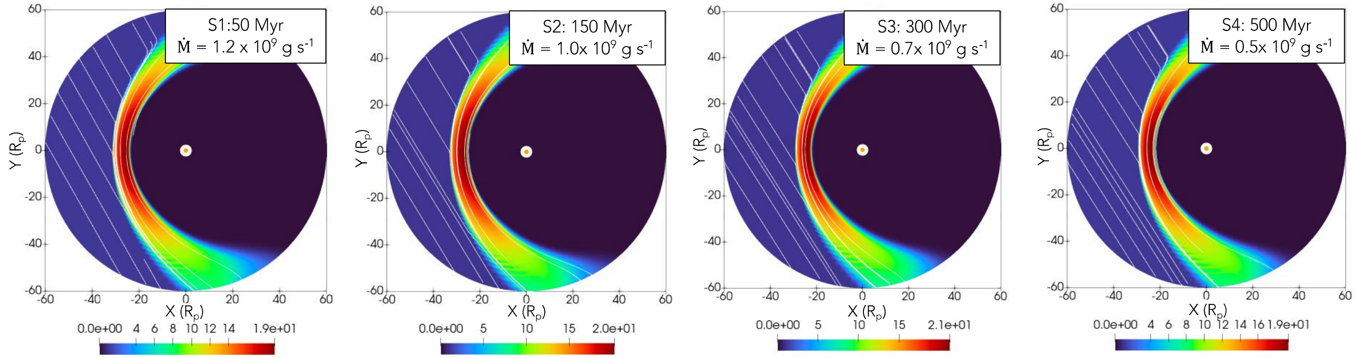
Results

FAST-ROTATING STARS



SLOW-ROTATING STARS



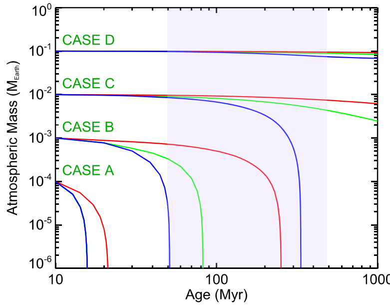
Results

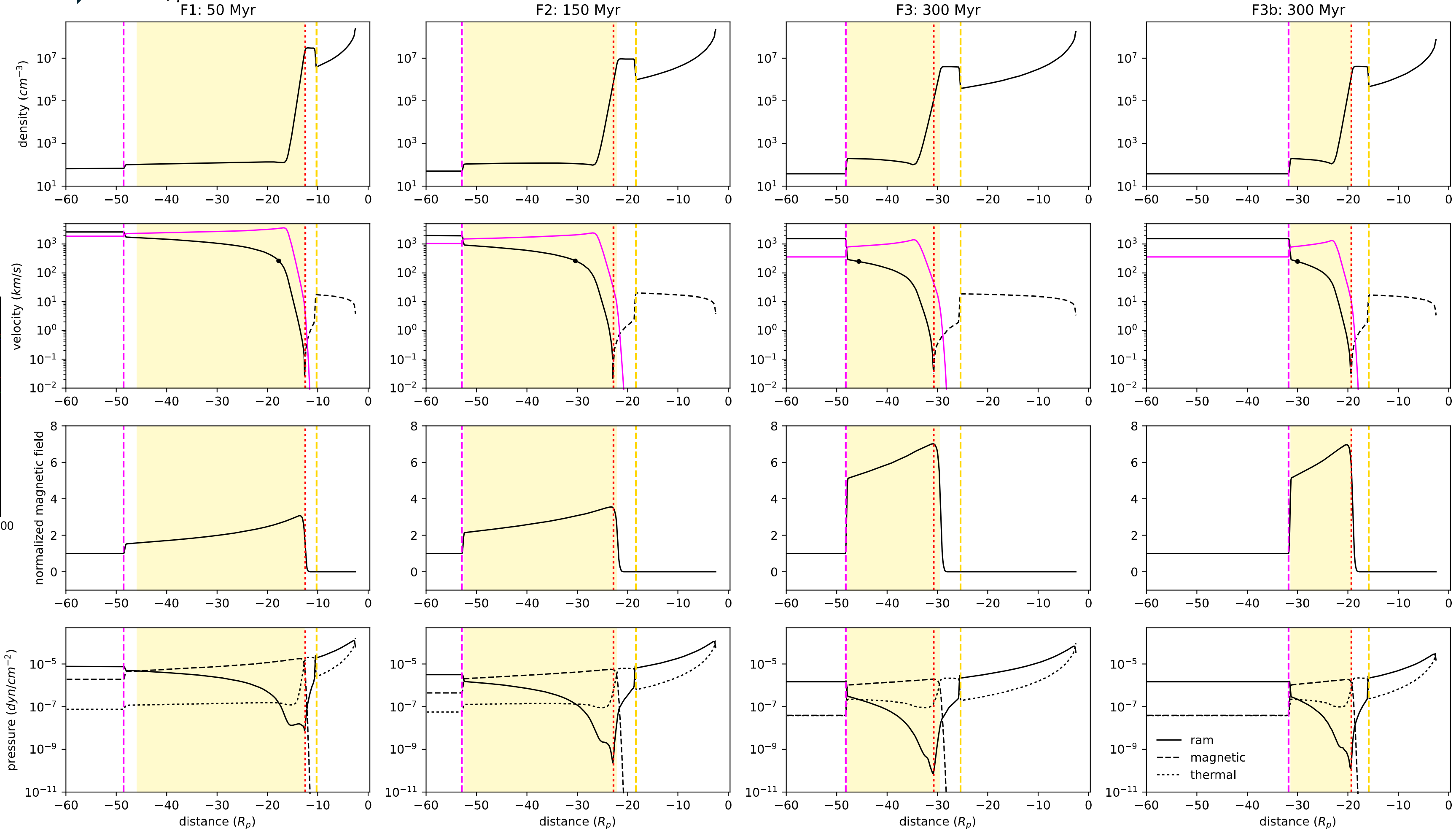
Fast-rotating stars: strong stellar winds

Stellar Wind → $P_{ram,\, sw}$ = 7.6x10^{-6} dyn cm^{-2} → x 0.4 → x 0.5 → x 1.0

Planetary Wind → $P_{ram,\, pw}$ = 9.4x10^{-5} dyn cm^{-2} → x 0.9 → x 0.7 → x 0.4

$$P_{ram} = \rho v^2$$



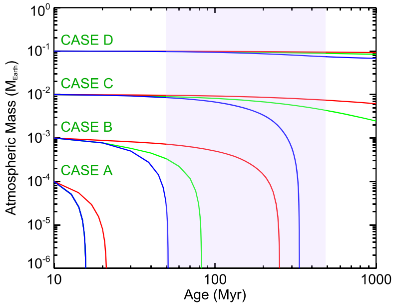


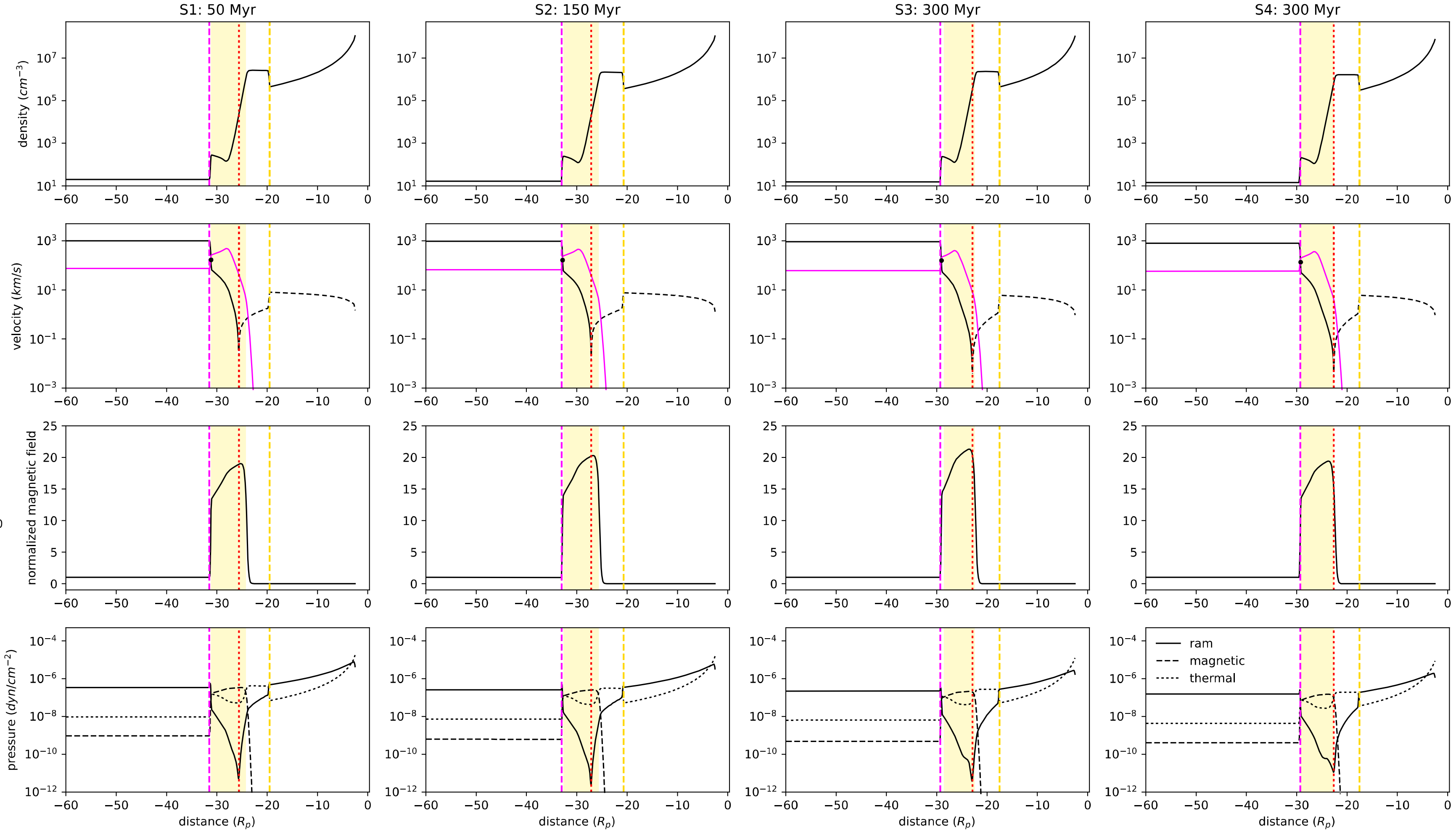
Results

Slow-rotating stars: faint stellar winds

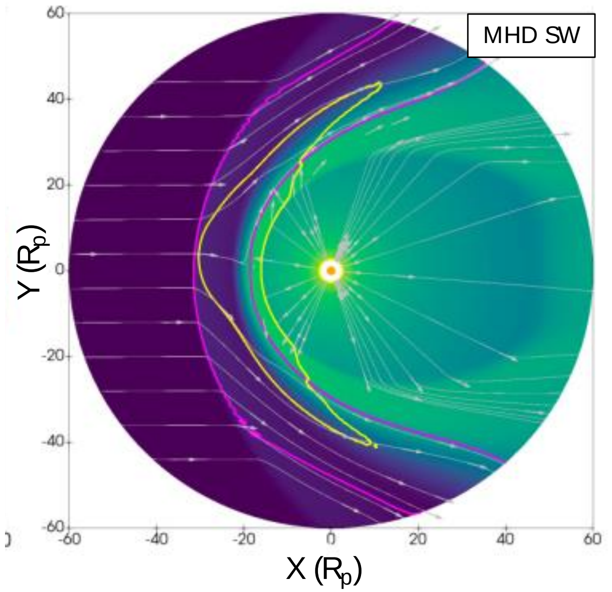
SW	$P_{ram,\, sw}$ = 3.4x10^{-7} dyn cm^{-2}	x 0.8	x 0.7	x 1.0
PW	$P_{ram,\, pw}$ = 9.4x10^{-5} dyn cm^{-2}	x 0.9	x 0.6	x 1.0

$$P_{ram} = \rho v^2$$





Results: Stellar wind driven atmospheric mass-loss

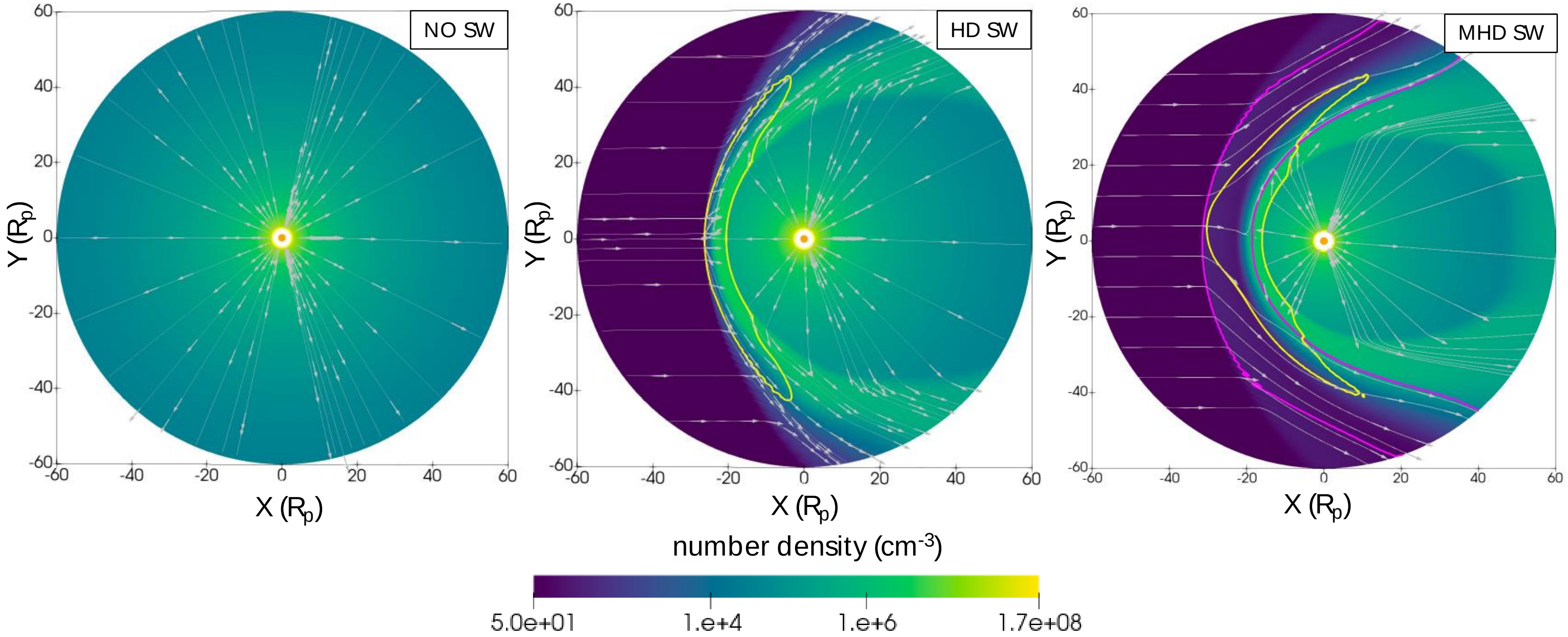


Increase of the atmospheric mass-loss rate

Fast-rotating stars: 1% (50 Myr), **4%** (150,300 Myr), 1% (F3b, 30 Myr)

Slow-rotating stars: 4% (50, 150 Myr), 2% (150,300 Myr)

Results: the interplanetary magnetic field



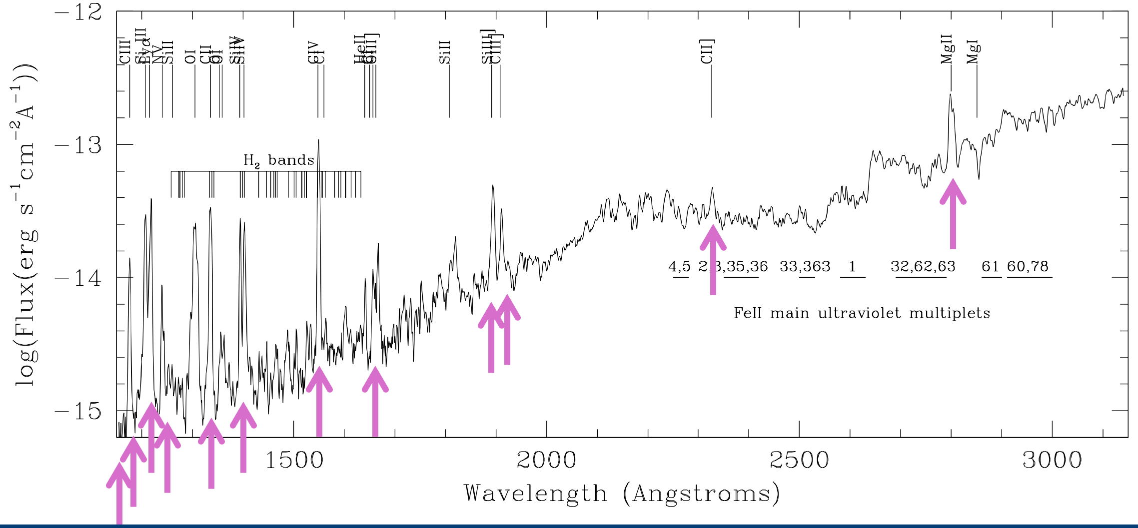
- 1.Introduction
- 2. Stellar Winds
- 3. Modelization
- 4. Results
- **5. Possible emission? Work in progress**
- 6. Conclusions

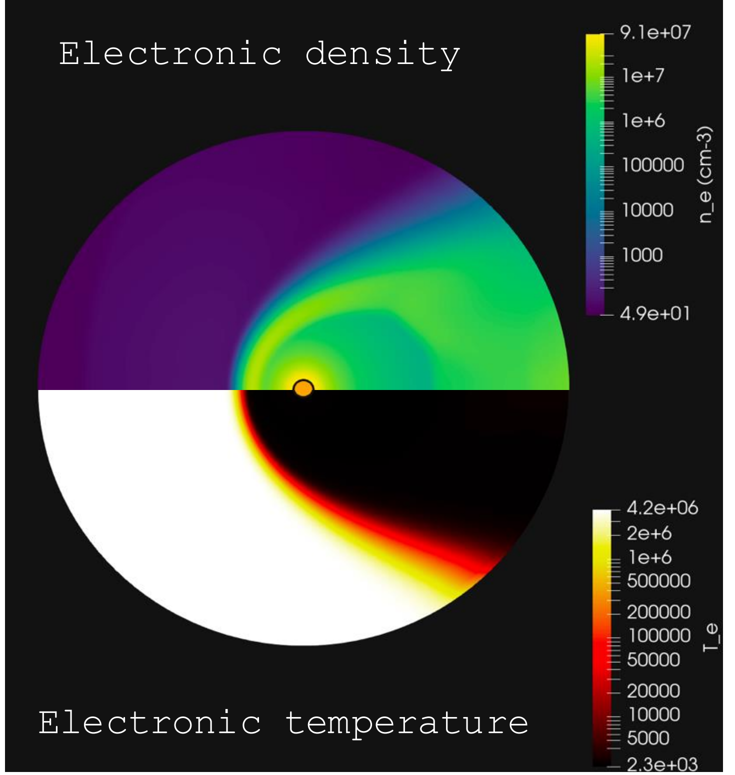
Possible double-shock emission Work in progress

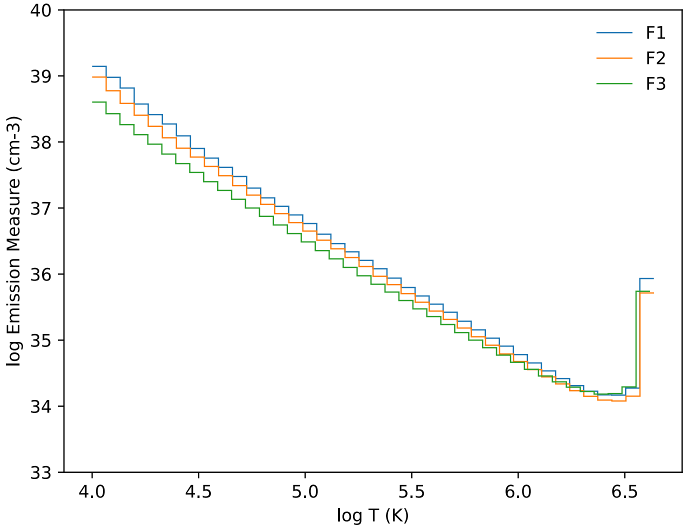
Emissivity calculation from PLUTO 3D maps

Atomic Database for Spectroscopic Diagnostics of Astrophysical Plasmas CHIANTI (Dere et al. 1997; Landi et al. 2013).

UV tracers: C III (117.57 nm), Si III (120.65 nm), **Ly-alpha (121.56 nm),** NV(123.88 nm), C II (133.45 nm), Si IV (139.38 nm), C IV (154.82 nm), He II (164.05 nm), Si III] (189.2 nm), C III] (190.87 nm), C II] (232.61 nm), **Mg II (279.64 nm)**

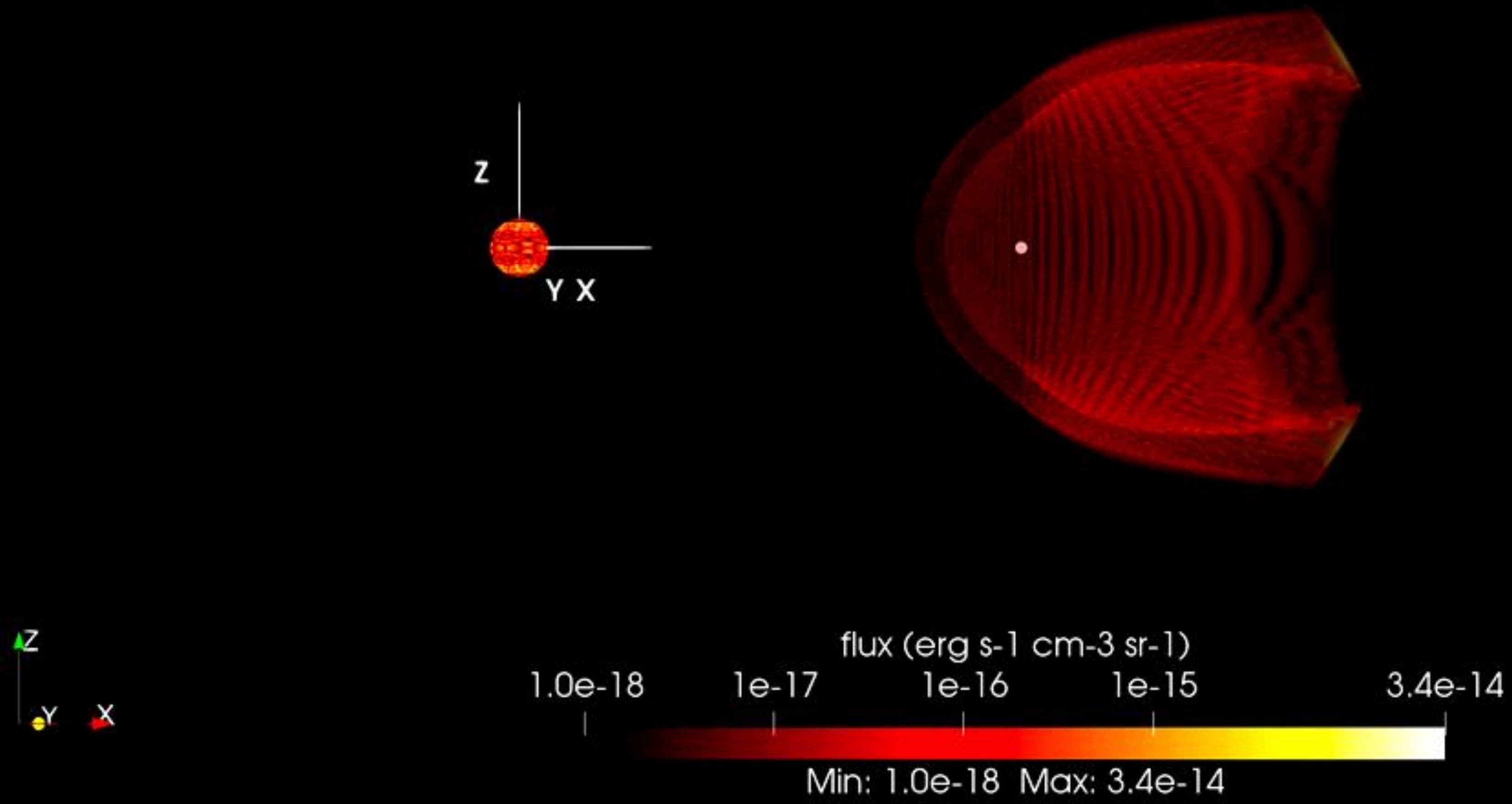






Ly-alpha emission

Planet in photoevaporation around a young **(50 Myr),** active star

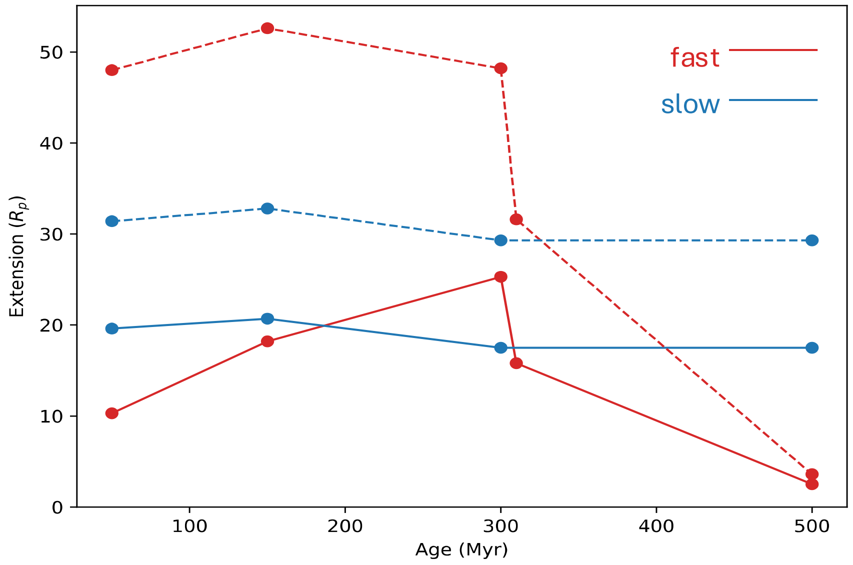


Conclusions

First study of the impact of stellar winds on the primordial atmospheres accreted by terrestrial planets: **Fast** and **slow** rotators.

Fast-rotating stars: Significant decrease (10 Rp) in extension at early ages (50 Myr), with an increase up to 300 Myr (25 Rp), and decrease in parallel to atmospheric loss (300 Myr). **Additional mass loss: 1% - 4%**

Slow-rotating stars: No significant changes in the evolution of atmospheres in the period between 50-500 Myr due to the action of stellar winds. Stable atmospheres with extension of ~20 Rp. **Additional mass loss : 2% - 4%**



Conclusions

- **Importance in detectability:** Decrease in excess absorption during the transit of the planet in the case of small atmospheres (fast-rotating stars).
- **Atmospheric mass-loss:** Small contribution compared to the atmospheric loss driven by the stellar XUV radiation.
- **Numerical simulations, including magnetic fields, are fundamental to predict atmospheric footprints around Earth-like planets**
- **Hot plasma accumulation in front of the planet may result in significant emission in UV tracers!!**

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