SIRIO: a public Python code to predict radio emission from (sub-Alfvénic) SPI

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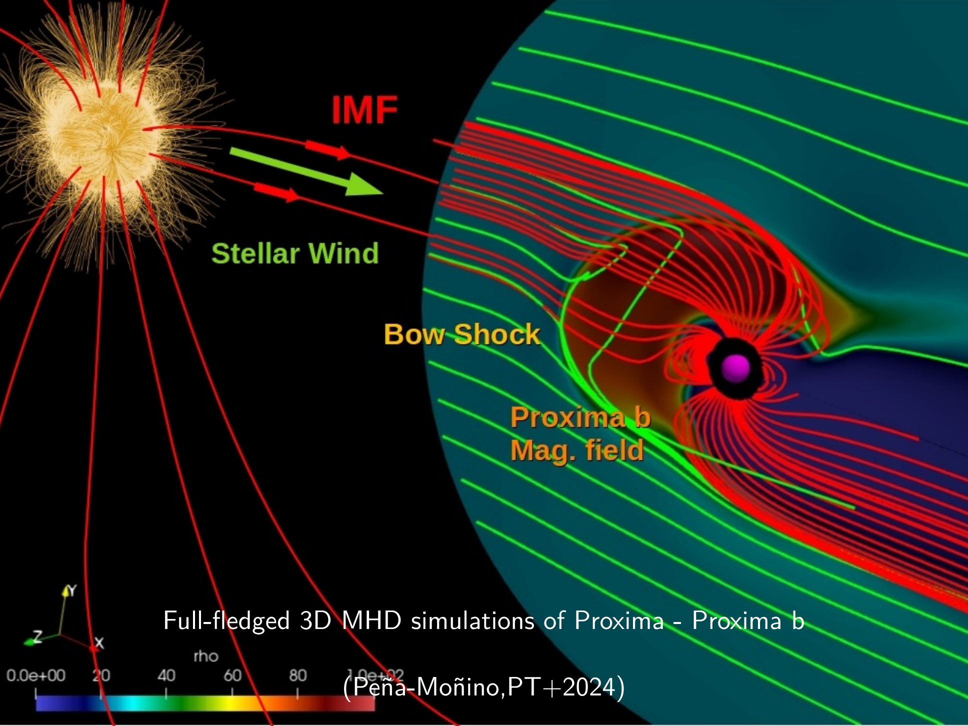


Full-fledged 3D MHD simulations of Proxima - Proxima b

(Peña-Moñino,PT+2024)

Using a sledgehammer to crack a nut?
(Tirer au canon sur une mouche)

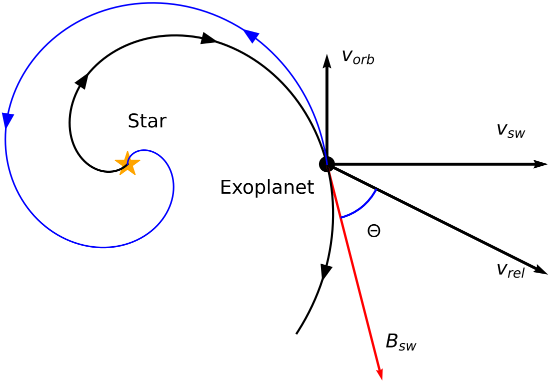
Full-fledged 3D MHD simulations

- Provide very detailed, precise information
- Very computationally expensive

SIRIO

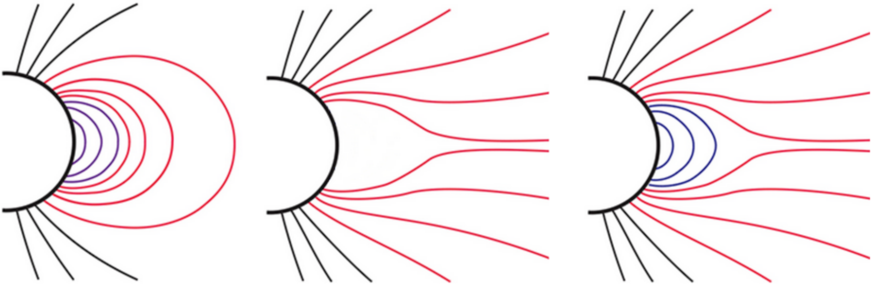
- Provides less detailed info
- Extremely cheap, computationally-wise

Sub-Alfvénic star-planet interaction



- $M_A = v_{\mathrm{rel}}/v_A < 1$
- $\vec{v}_{\mathrm{rel}} = \vec{v}_{\mathrm{w}} - \vec{v}_{\mathrm{orb}}$
- $v_{\mathrm{A}} = B_{\mathrm{sw}}/(4\,\pi\,\rho_{\mathrm{w}})^{1/2}$

Stellar wind magnetic field geometry



(Owens+2020)

Radio power from star-planet interaction

Alfvén wing model (e.g., Zarka 2007, Saur 2013)

- $S_{\mathrm{Alf}} = 2\,\pi\,R_{\mathsf{eff}}^2 \frac{(\overline{\alpha}\,M_{\mathrm{A}}\,B_{\mathrm{sw}}\ \sin\Theta)^2}{\mu_0}\,v_{\mathrm{A}}$

Reconnection model (Lanza 2009)

- $S_{\mathrm{rec}} = \frac{\gamma\pi}{\epsilon\,\mu_0} B_{\mathrm{sw}}^2 R_{\mathsf{mp}}^2 v_{\mathrm{rel}}$

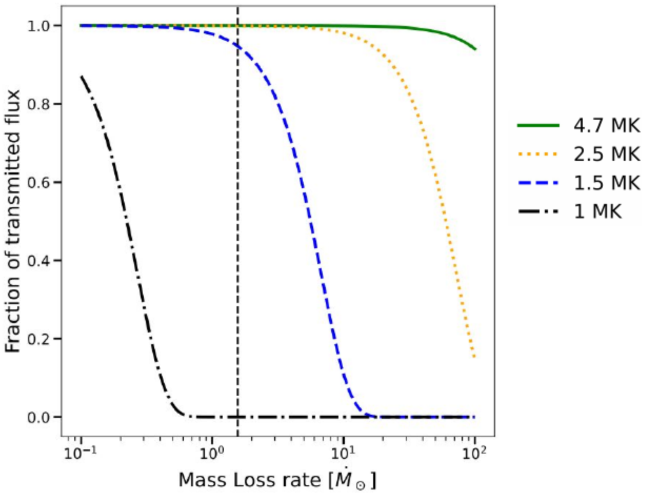
Poynting fux ratio

- $\frac{S_{\mathrm{rec}}}{S_{\mathrm{Alf}}} = \frac{\gamma}{2\,\epsilon\,\overline{\alpha}^2\,M_{\mathrm{A}}\,\sin^2\Theta}$

Observed radio flux density

- $F_R = \frac{P_R}{\Omega\,D^2\,\Delta\nu}$

Free-free absorption from the stellar wind



- $\tau_\nu = \int_{R_\star}^{\infty} \kappa_\nu \, dz$
- $\kappa_\nu = 3.692 \times 10^8 \left(1 - e^{-h\nu/k_B T}\right) Z^2 \, g T^{-1/2} \, \nu^{-3} \, n_e \, n_p$

Effective radius and exoplanetary magnetic field

Effective radius of exoplanet

- $R_{\mathsf{mp}} = k_{\mathsf{mp}}^{1/3} \left[\frac{(B_{\mathrm{p}}/2)^2/8\pi}{\rho_{\mathrm{sw}} v_{\mathrm{rel}}^2 + n_{\mathrm{sw}} k_B T_e + B_{\mathsf{sw}}^2/8\pi} \right]^{1/6} R_{\mathsf{pl}}.$

Exoplanetary magnetic field

- $B_{\mathsf{pl}} = \mathfrak{M}/R_{\mathsf{pl}}^3$
- $\mathfrak{M} \propto \Omega_{\mathrm{pl}}\, \rho_{\mathrm{core}}^{1/2}\, r_{\mathrm{core}}^{7/2}$ (Sano 1993)

SIRIO - (Paper submitted to MNRAS a month ago)

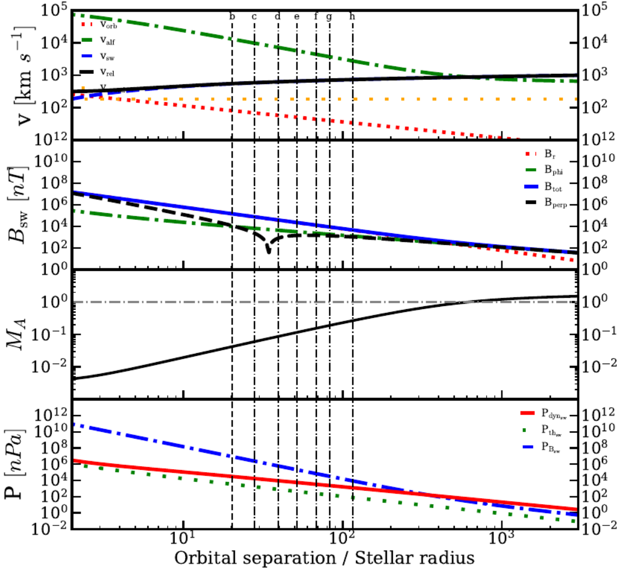
Code input/assumptions/approximations:

- Sub-Alfvénic star-planet interaction
- Isothermal stellar wind
- Three stellar wind magnetic field geometries: Open, closed, hybrid
- Radio emission: Alfvén wing and reconnection models
- Free-free absorption from the stellar wind
- Exoplanetary magnetic field and effective radius
- Input stellar data: $M_\star, R_\star, P_{\rm rot}, B_\star,\ T_{\rm wind},\ \dot{M}_\star$
- Input planetary data: $M_{\rm pl}, R_{\rm pl}, P_{\rm orb}, B_{\rm pl}$ (computed using Sano's law).

Code output:

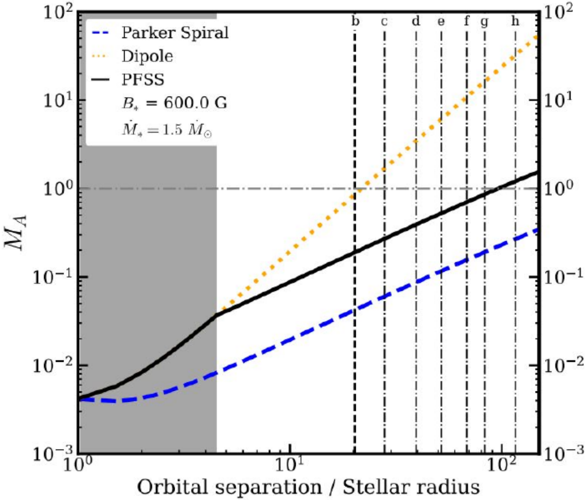
- Predicted flux density as a function of orbital separation $\Rightarrow$ Useful for both confirmed and unconfirmed planets
- Predicted flux density as function of $\dot{M}_\star$ and $B_{\rm pl}$ $\Rightarrow$ Constraints on $\dot{M}_\star$ and $B_{\rm pl}$

TRAPPIST-1 - Diagnostic plots



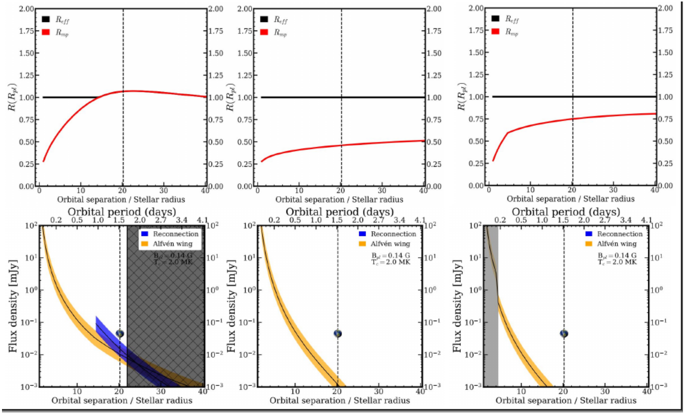
- Benchmark - // Turnpenney+2018
- Diagnostic plots
- Open Parker spiral
- Fiducial values: $B_\star = 600$ G; $B_{\rm pl} = 0.14$ G; $\dot{M}_\star = 1.5\dot{M}_\odot$.

TRAPPIST-1 - Alfvén Mach number



- Dipole ⇒ All planets outside Alfvén surface
- Open ⇒ All planets within Alfvén surface
- Hybrid ⇒ Several planets within Alfvén surface

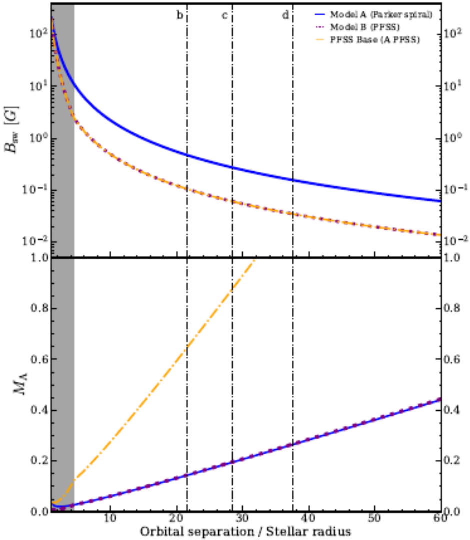
TRAPPIST-1 - Effective radius



Effective radius of exoplanet

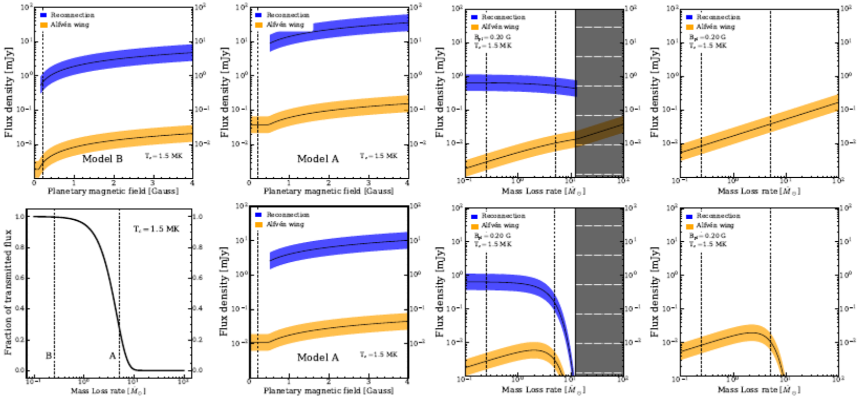
- Alfvén wing: $R_{\text{eff}} = max(R_{\text{mp}}, R_{\text{pl}})$
- Reconnection model: $R_{\text{eff}} = R_{\text{mp}}$ (if $R_{\text{mp}} \geqslant R_{\text{pl}}$); otherwise, $R_{\text{eff}} = 0$.

YZ Ceti - M_{A} and B_{sw}



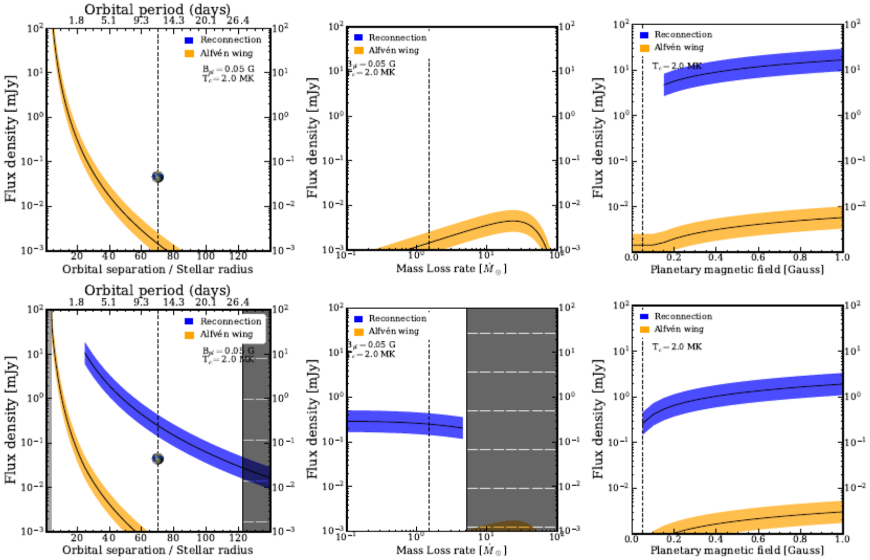
- Benchmark - Pineda & Villadsen (2023)
- Two models (high mass-loss and low mass-loss rate)
- Hybrid magnetic field geometry for the stellar wind

YZ Ceti - Flux density vs $\dot{M}_\star$ and $B_{\rm pl}$



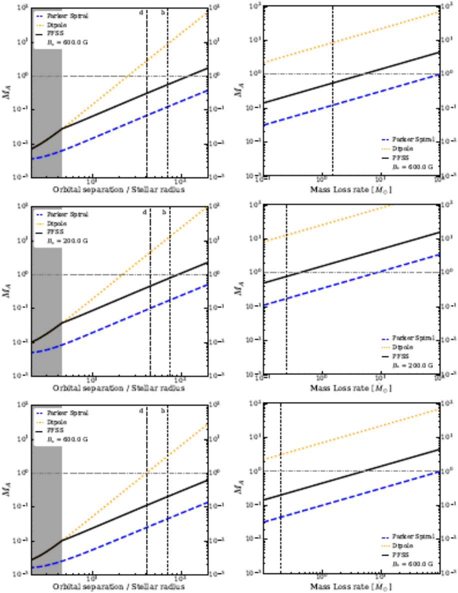
- Fiducial values $B_\star = 220$ G; $B_{\rm pl} = 0.20$ G
- Model A: $\dot{M}_\star = 5.0\ \dot{M}_\odot$; Model B: $\dot{M}_\star = 0.25\ \dot{M}_\odot$
- Reconnection model predicts much higher flux densities
- Free-free absorption effects

Proxima - Proxima b: Flux density vs. $\dot{M}_\star$ and B_{pl}



- Fiducial values: $B_\star = 600$ G; $B_{pl} = 0.05$ G; $\dot{M}_\star = 1.5\dot{M}_\odot$.

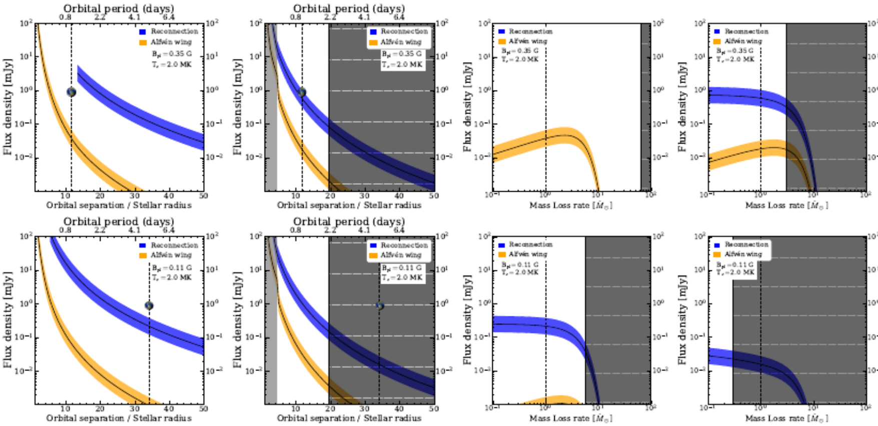
Proxima - Proxima b:Alfvén Mach number vs orbital separation



Comparison of different models proposed for Proxima

- Top: Turnpenney+2018 ($B_\star = 600$ G; $B_{\mathrm{pl}} = 0.05$ G; $\dot{M}_\star = 1.5\dot{M}_\odot$)
- Middle: Kavanagh+2021 ($B_\star = 200$ G; $B_{\mathrm{pl}} = 0.05$ G; $\dot{M}_\star = 0.25\dot{M}_\odot$)
- Bottom: Réville+2024($B_\star = 600$ G; $B_{\mathrm{pl}} = 0.05$ G; $\dot{M}_\star = 0.20\dot{M}_\odot$)

GJ 1151 - GJ 1151b: Flux density vs. $\dot{M}_\star$ and B_{pl}



- Top panels: $B_\star = 50$ G; $B_{pl} = 0.35$ G ($M_{pl} = 0.73\,M_\odot$)
- Bottom panels: $B_\star = 50$ G; $B_{pl} = 0.11$ G ($M_{pl} = 1.25\,M_\odot$)
- Predictions of reconnection model compatible with LOFAR radio detection. They favour the closest planet scenario.

Summary

Paper submitted to MNRAS. Reviewer's report was due yesterday...

SIRIO code

- Public Python code to model radio emission from SPI
- Sub-Alfvénic SPI
- Isothermal stellar wind
- Different stellar wind geometries
- Free-free absorption

Case studies

- TRAPPIST-1
- YZ Ceti
- Proxima Cen
- GJ 1151

SIRIO - less accurate than 3D MHD simulations, but very efficient to run on many sources, in preparation for proposals