Victor Réville, Irfu SAp,

Laboratoire Dynamique des étoiles et de leur environnement (LDEE) avec Sacha Brun.

ENSTA ParisTech / Master Modélisation et Simulation

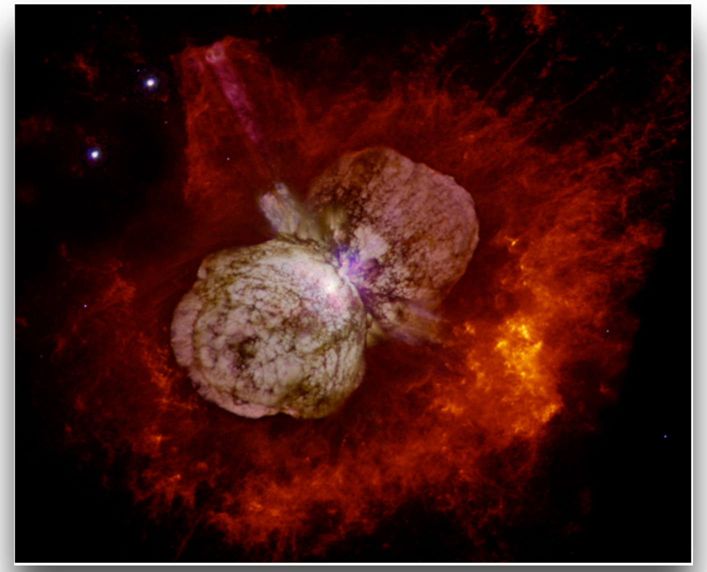
Cours d'Astrophysique du master

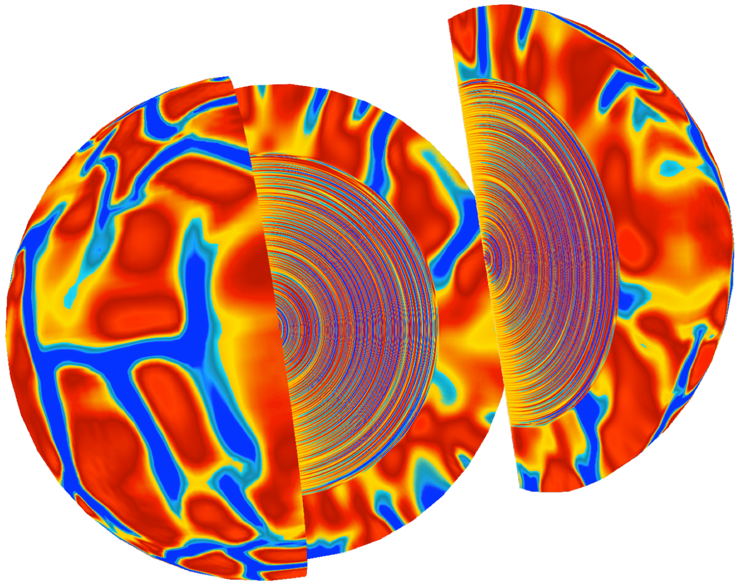
Motivations : *faire de la recherche, exploiter et approfondir mes connaissances en mathématiques appliquées et numériques, apprendre et découvrir de nouveaux domaines.*

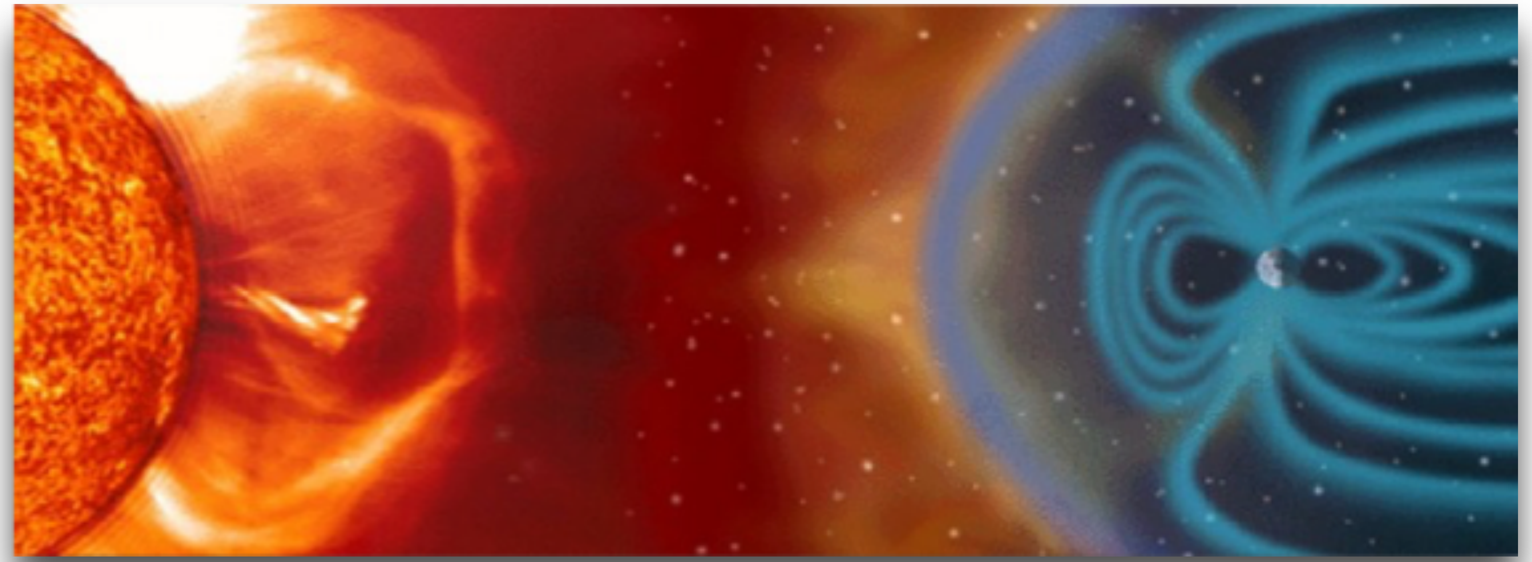
Exoplanètes, physique stellaire

Intéractions étoiles-planètes : influence du magnétisme stellaire sur les conditions d'habitabilité des (exo)planètes.

- Stellar Magnetism / Dynamo
- Stellar Winds / Magnetic Braking / Mass Loss
- Planetary Magnetosphere





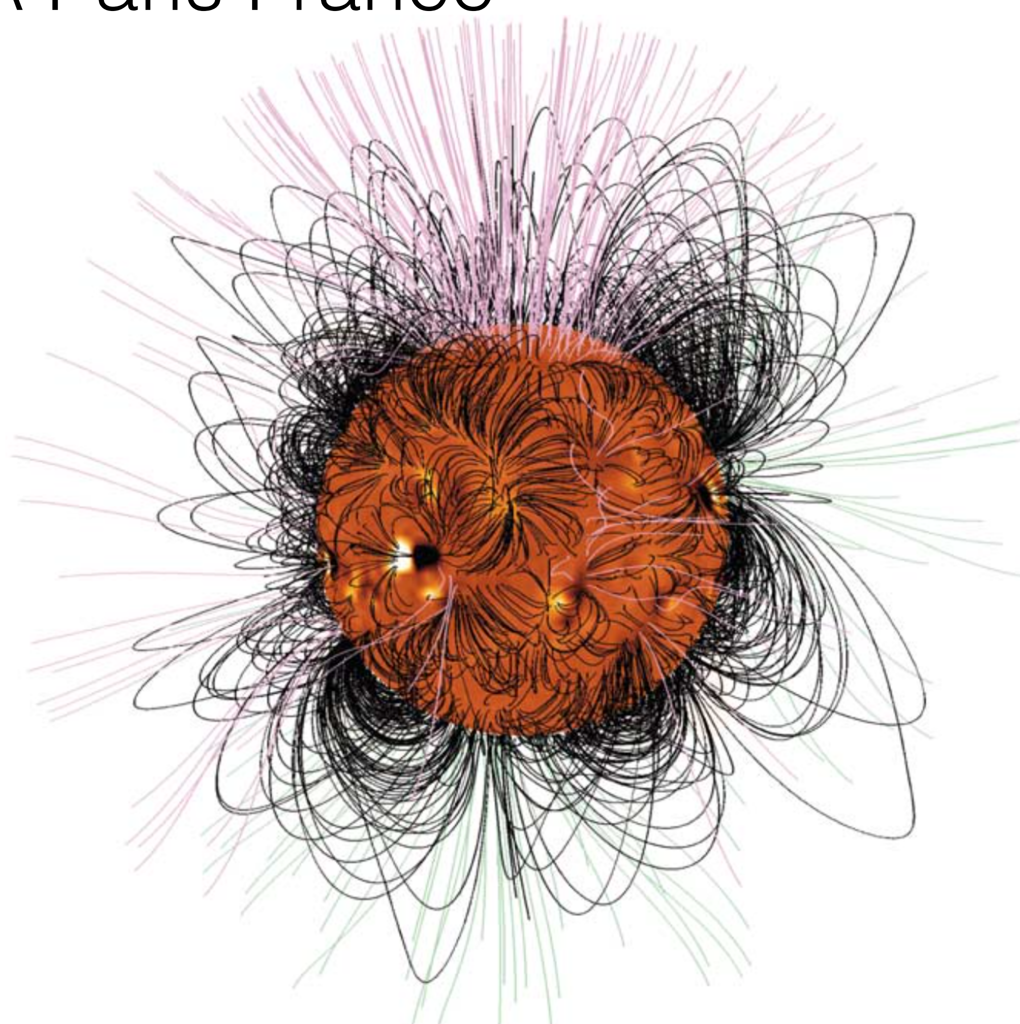


Stellar winds and their influence on stellar evolution and habitability

Victor Réville, Sacha Brun

Antoine Strugarek, Sean Matt, Rui Pinto, Jérôme Bouvier, Colin Folsom, Pascal Petit, Jacobo Varela

PhD, Laboratoire dynamique des étoiles et de leur environnement
AIM Paris-Saclay/CEA Paris France



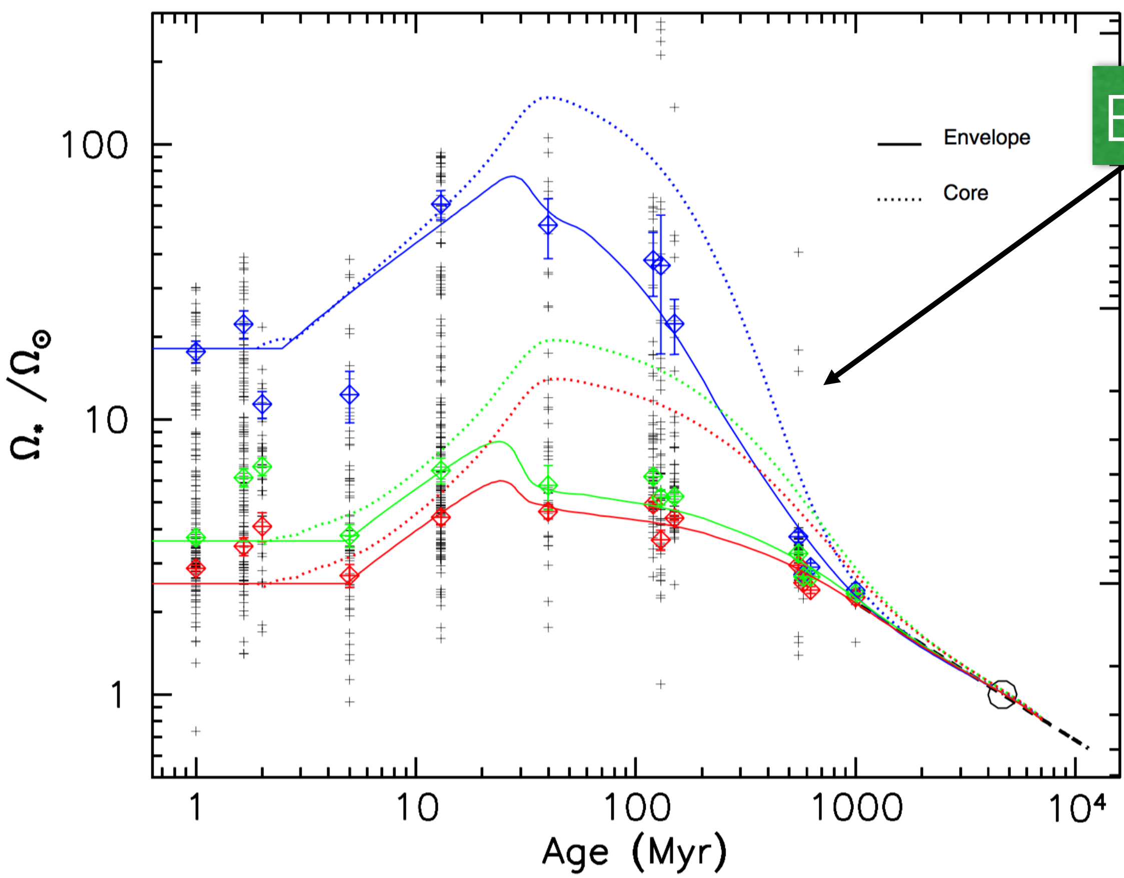
Irfu

DE LA RECHERCHE À L'INDUSTRIE
cea

DDays, July 1st 2015

Winds and stellar evolution
gyrochronology

Rotation Models
Gallet & Bouvier 2013

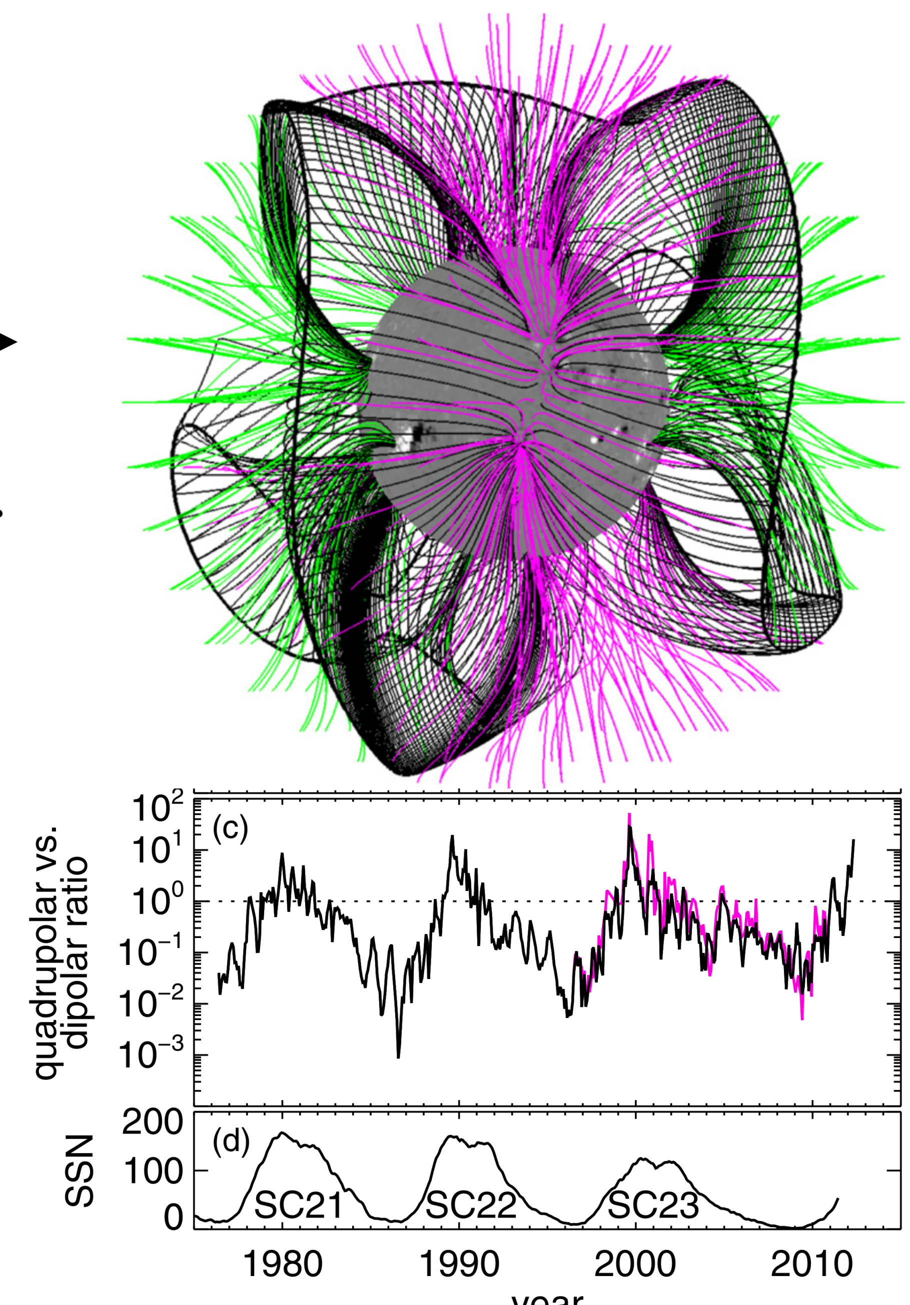


Braking models

dynamo

wind

Magnetic Activity
De Rosa, Brun, Hoeksema 2012



Skumanich's law: $\Omega_* \propto t^{-1/2}$

MHD Wind Theory

Parker (1958)

1D, Hydro, Isothermal Solution

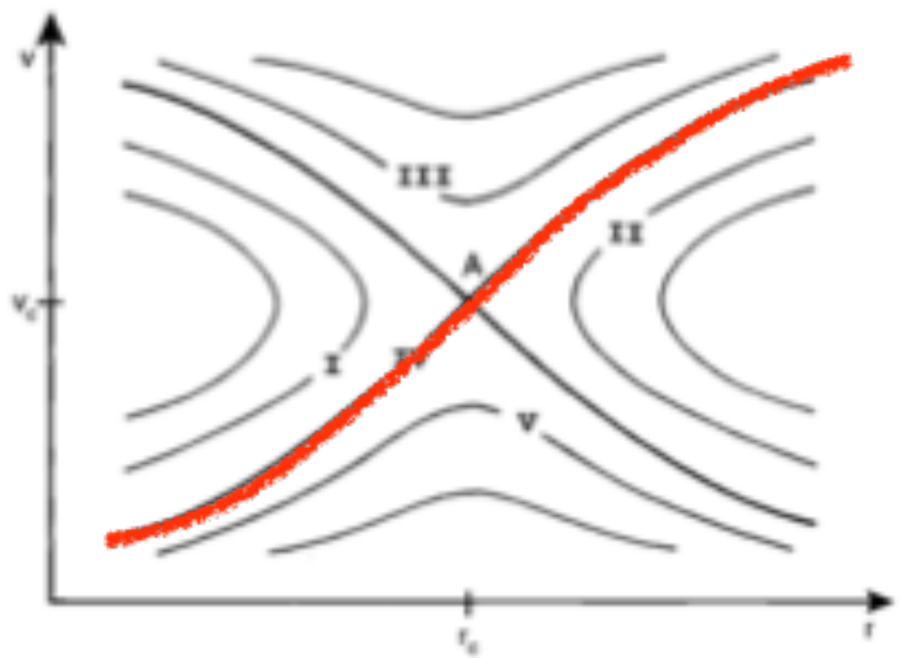
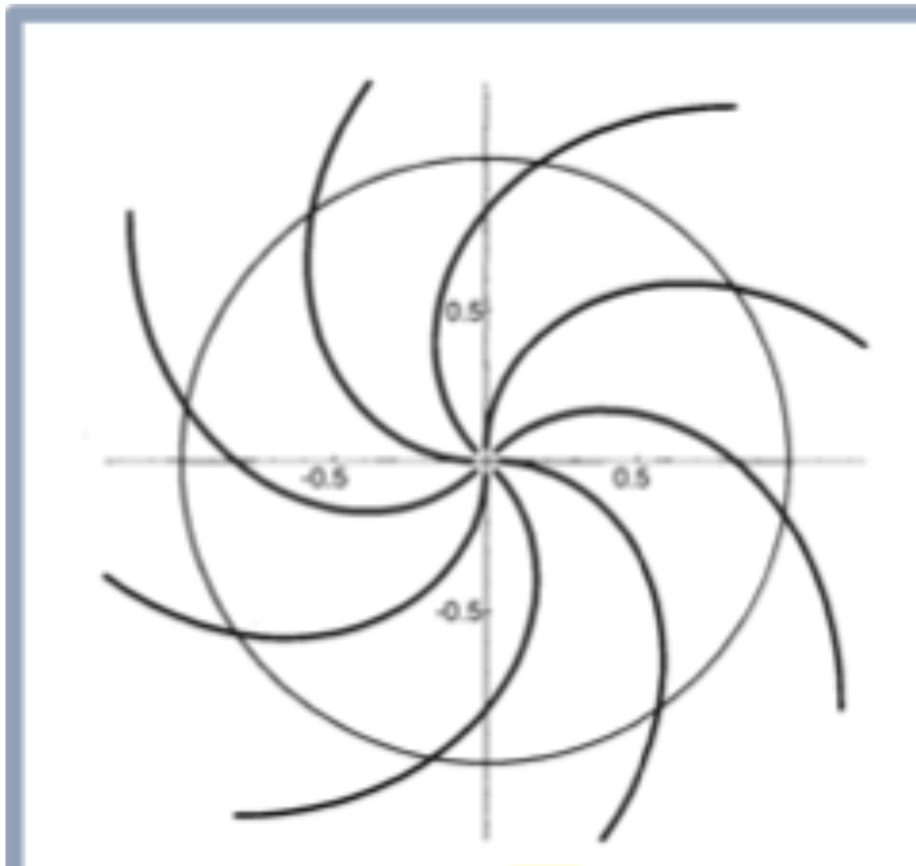


Figure 12.1 Mathematically admissible classes of isothermal solutions of an expanding corona.

Weber & Davis (1967)

Lever arm



Why ?

P_hydrostat = 10^-4 Psurf
P_obs = 10^-14 Psurf

Angular momentum loss

$$\frac{dJ}{dt} = \frac{dM}{dt} L = \frac{dM}{dt} r_A^2 \Omega$$

Spin down through magnetic braking (Schatzmann 1962)

MHD Wind Theory

MHD Wind Simulations

Why are they necessary ?

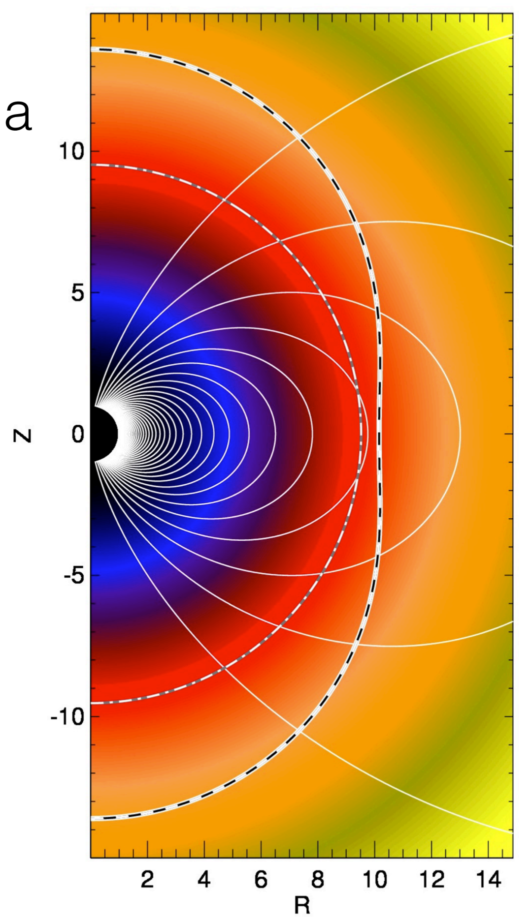
- Magnetic fields > split monopole
- Rotation
- 3D, non-axisymmetry

Decreasing Alfvén surface !

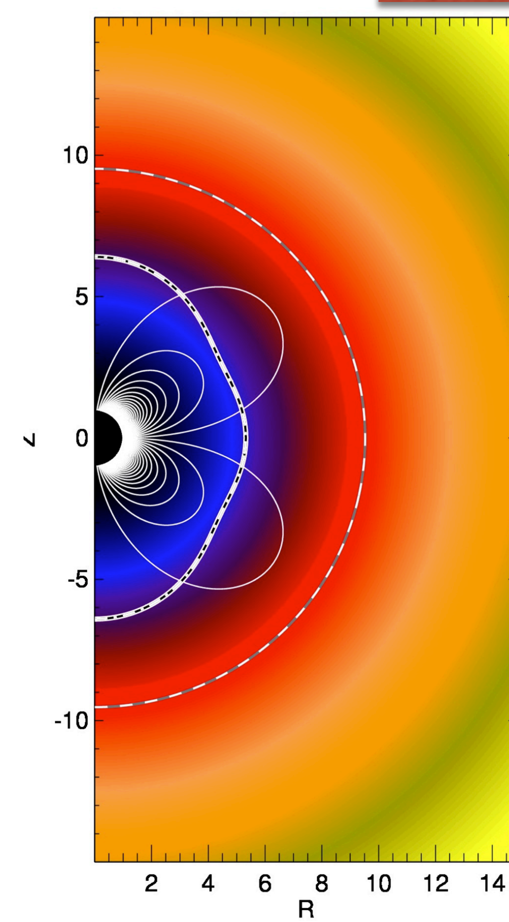
Parametric study of the torque as a function of:

- Rotation
- Magnetic field strength
- Magnetic field topology

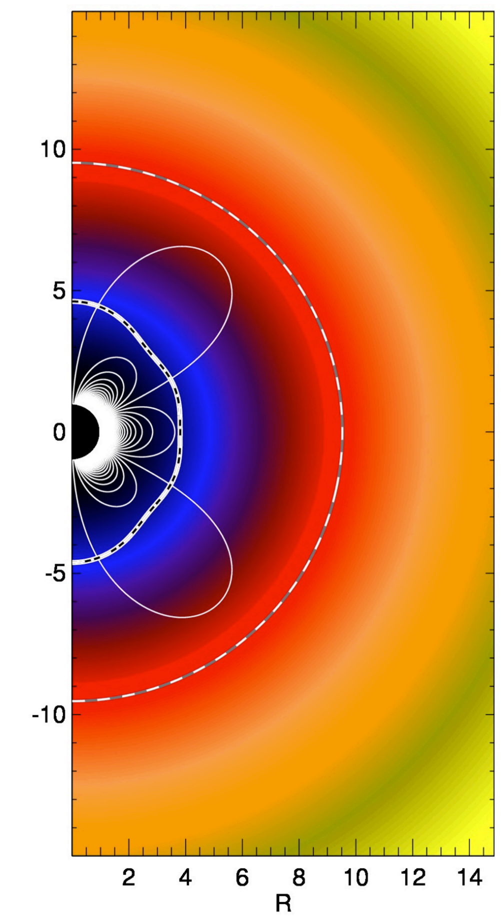
Coronal temperature and gamma held fixed.



Dipole



Quadrupole



Octupole

60 cases with compressible MHD code PLUTO

Réville et al. 2015, ApJ 798:116

Technical Stuff

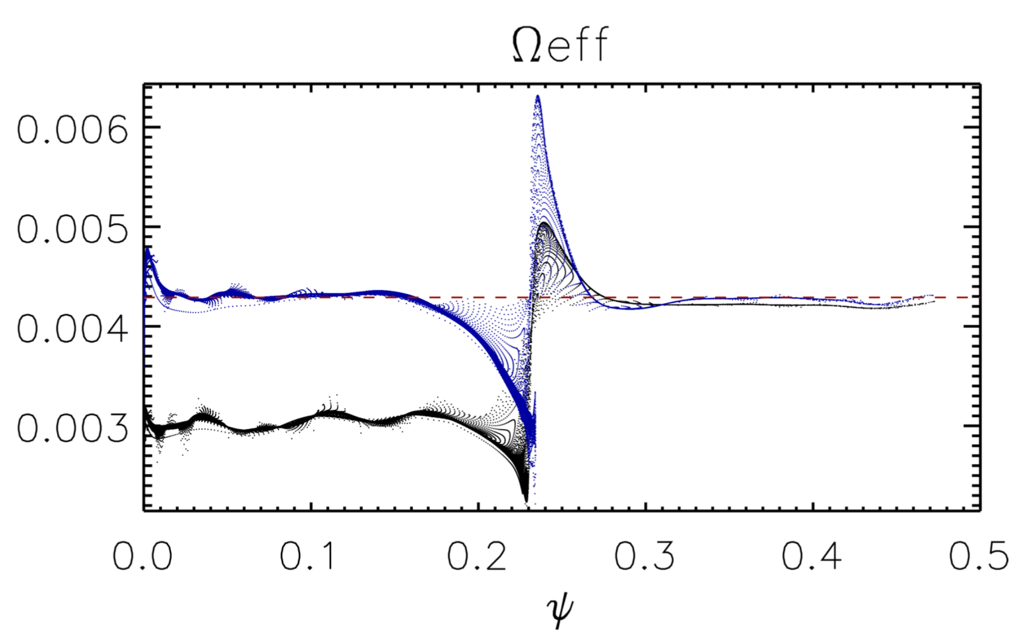
2D and 3D simulations

PLUTO Code

Mignone 2007 (University of Torino)
Parallel Compressible MHD code:

Ideal MHD
Cylindrical grid 2D / Cartesian grid 3D
20k to 100k core-hours on
Turing (blue gene q IDRIS)

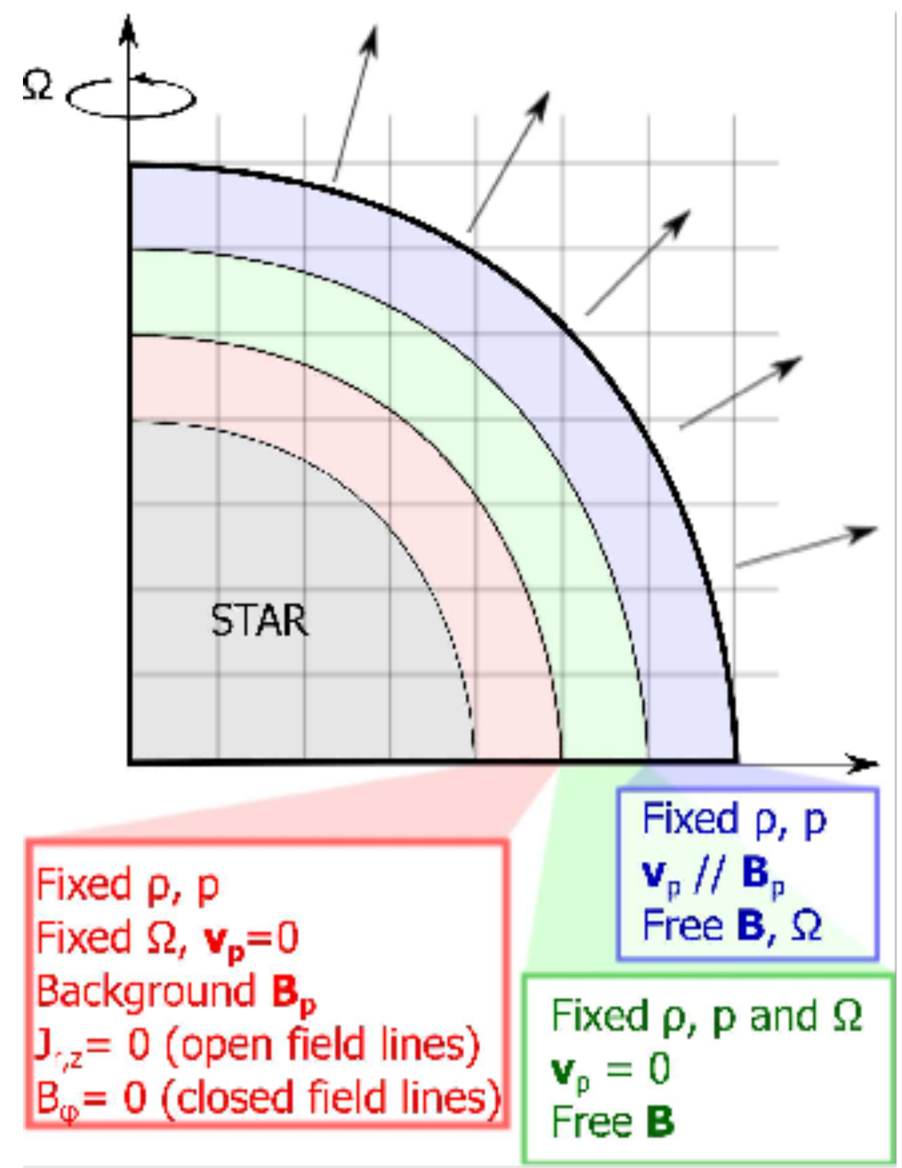
Development of wind setup from scratch with A. Strugarek and S. Matt.



Boundary conditions:

critical for angular momentum calculations

$$\Omega_{\rm eff}(\psi) \equiv \frac{1}{R}\left(v_\phi - \frac{v_p}{B_p}B_\phi\right)$$



MHD Wind Simulations

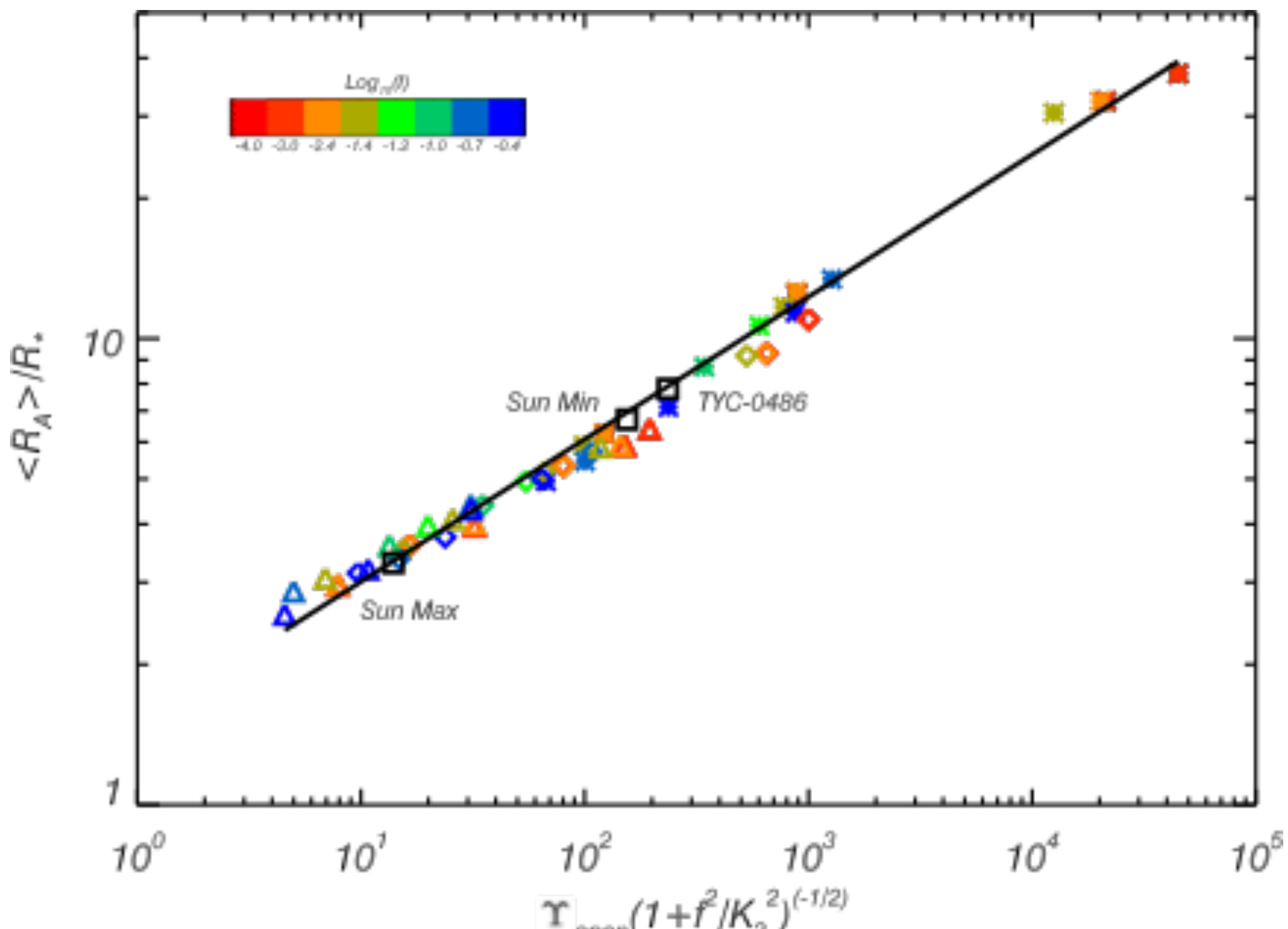
The most general law as of today:

$$\frac{dJ}{dt} = \frac{dM}{dt}\Omega_* < r_A^2 >$$

open flux

$$\Phi_{open} = \int_S |\vec{B} \cdot d\vec{S}|$$

$$\frac{dJ}{dt} = \frac{dM}{dt}^{1-2m} \Omega_* R_*^{2-4m} K_1^2 \Phi_{open}^{4m} (1 + f^2 / K_2^2)^{-m} v_{esc}^{-2m}$$



m=0.3
K1=1.4
K3=0.05

Réville et al. 2015, ApJ 798:116

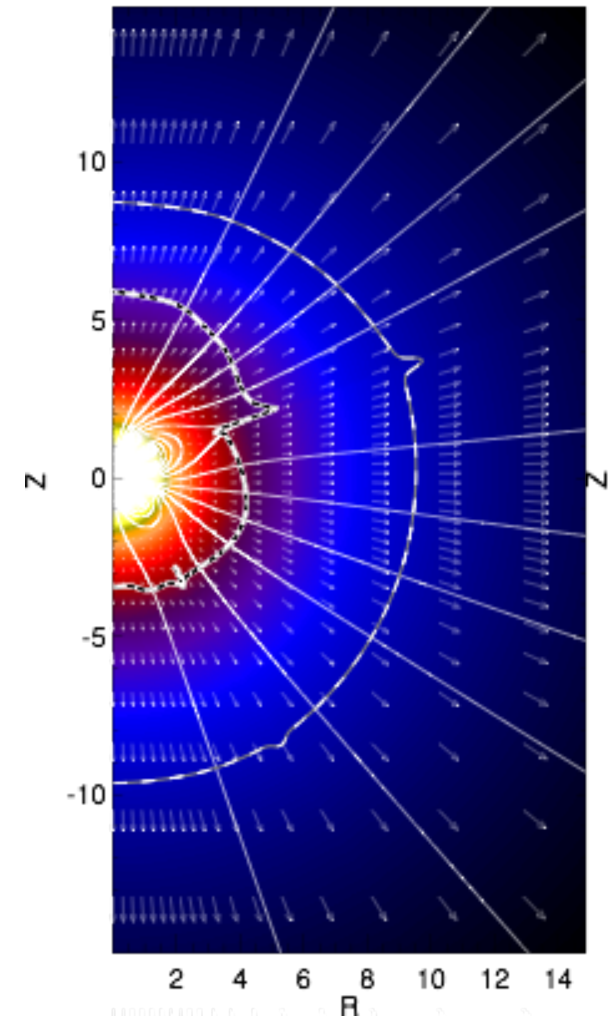
Surface magnetic field and Zeeman Doppler Imaging

Spectropolarimeters:

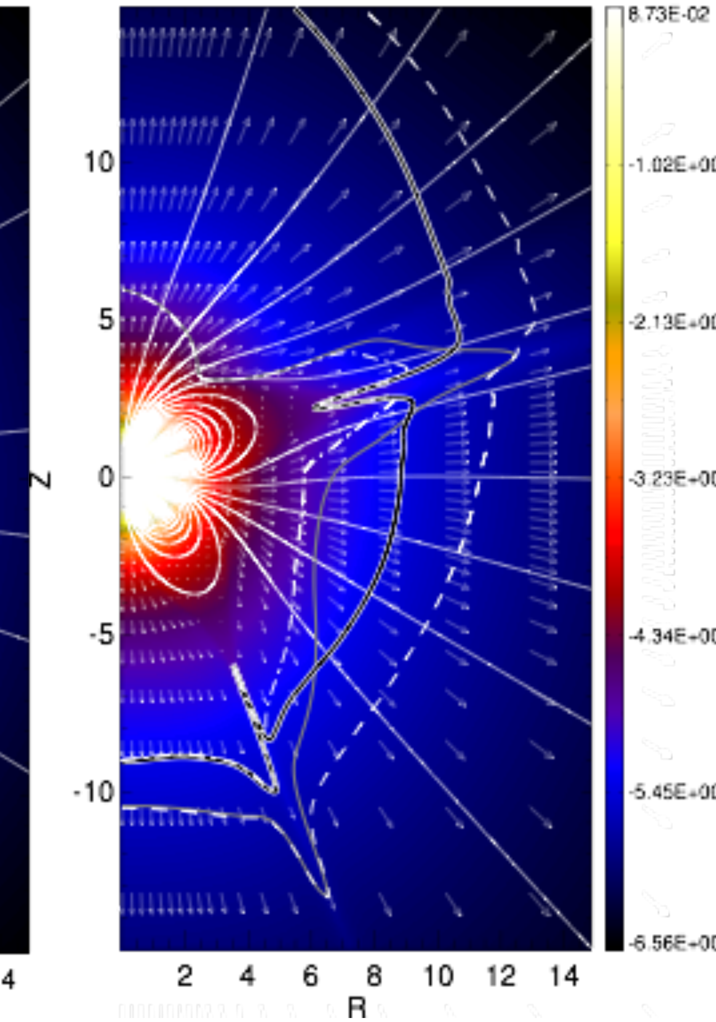
Narval 375nm à 1050nm @TBL
& Espadons (370nm à 1000 nm) @CFHT

Zeeman Doppler Imaging consist in extracting Stokes parameters as a function of phase, on several wave-lengths to increase signal over noise ratio.

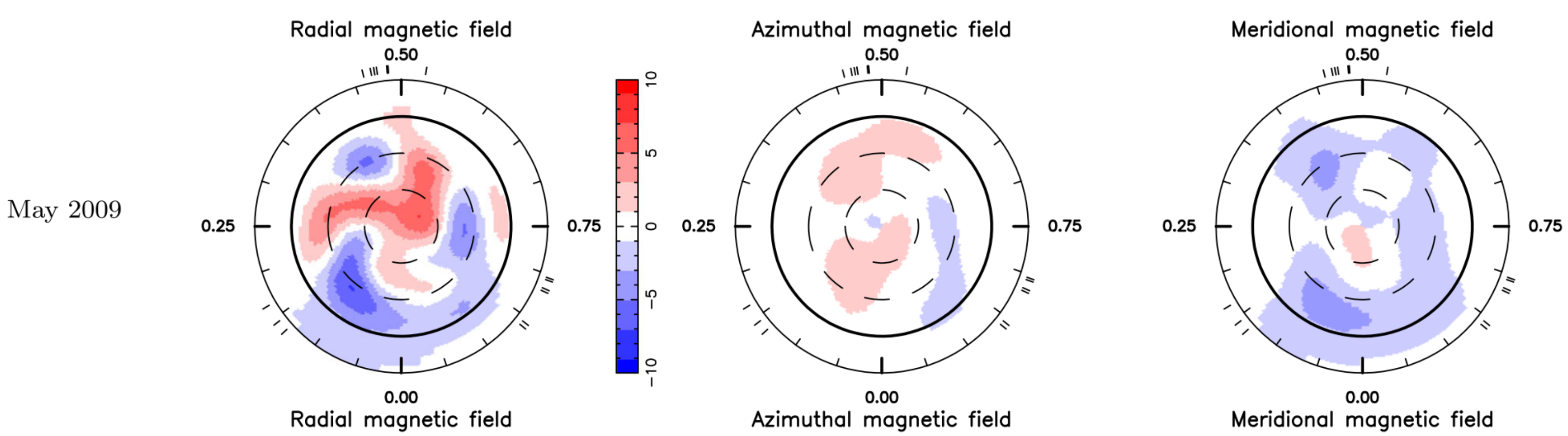
Works well on fast rotators.



The Sun at maximum of cycle 22



Young K-Star TYC-0486-4943-1



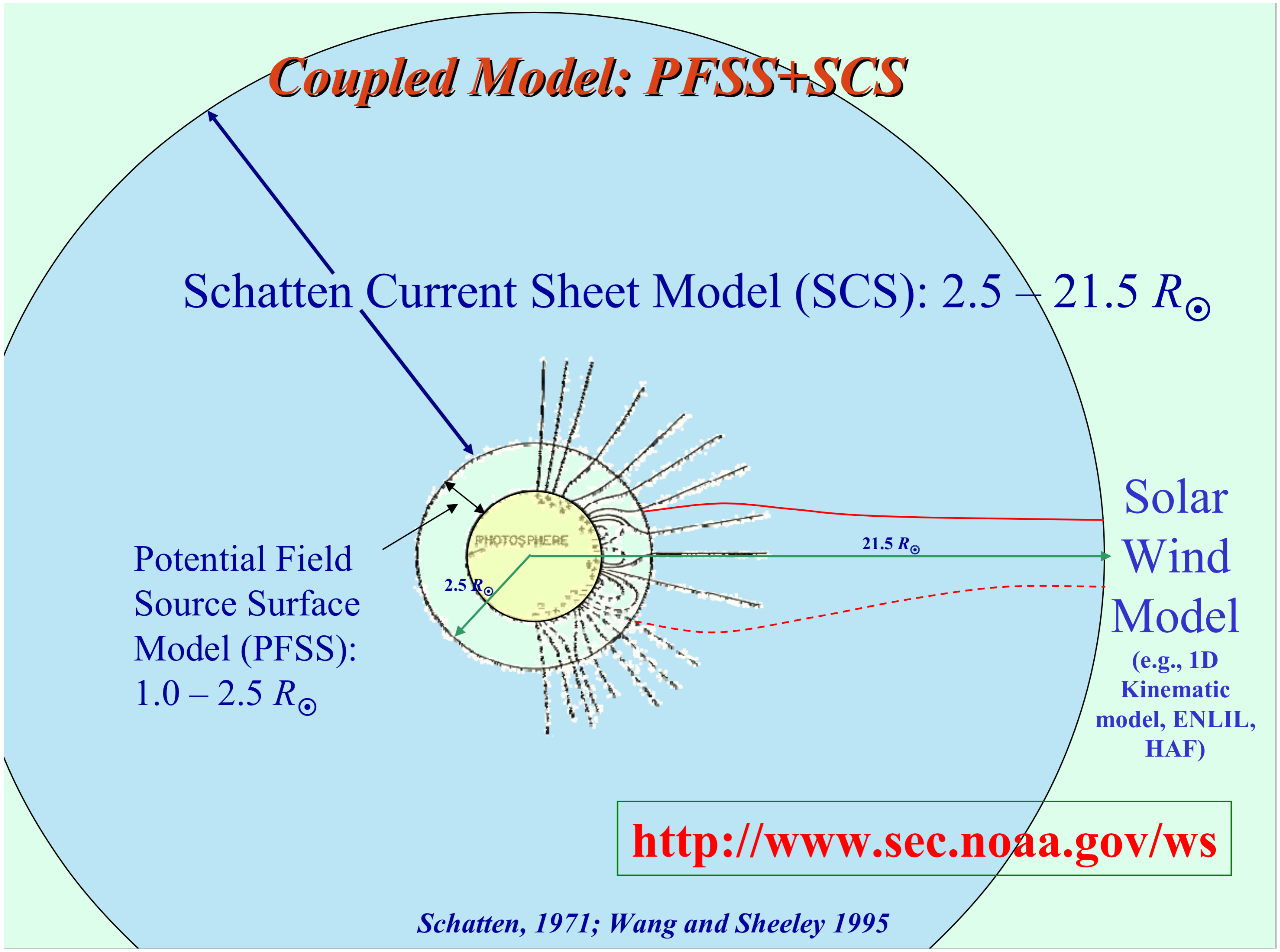
Tau Boo by Fares et al. 2013

Regression methods ->

List of spherical harmonics decomposition coefficients.

How to estimate the open flux ?

Take inspiration from Solar physics:



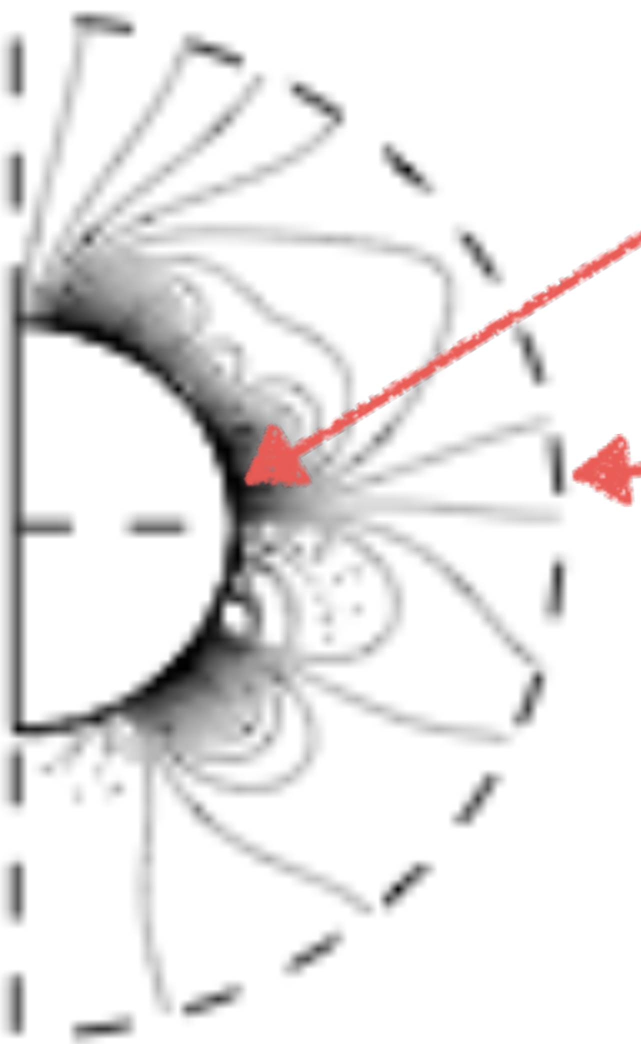
Potential Extrapolation

$\nabla \times \mathbf{B} = 0$ $-\nabla\Phi = \mathbf{B}$ *Current free 1<r< Rss*

The potential is solution of Laplace's equation: $\Delta\Phi = 0$

$$\left.\frac{\partial\Phi}{\partial r}\right|_{r=1} = -B_r(1, \theta', \phi),$$

$$\Phi = 0 \quad \text{at} \quad r = R_{ss}$$



The field is potential between the stellar surface and a source surface, radial beyond.

Potential Extrapolation

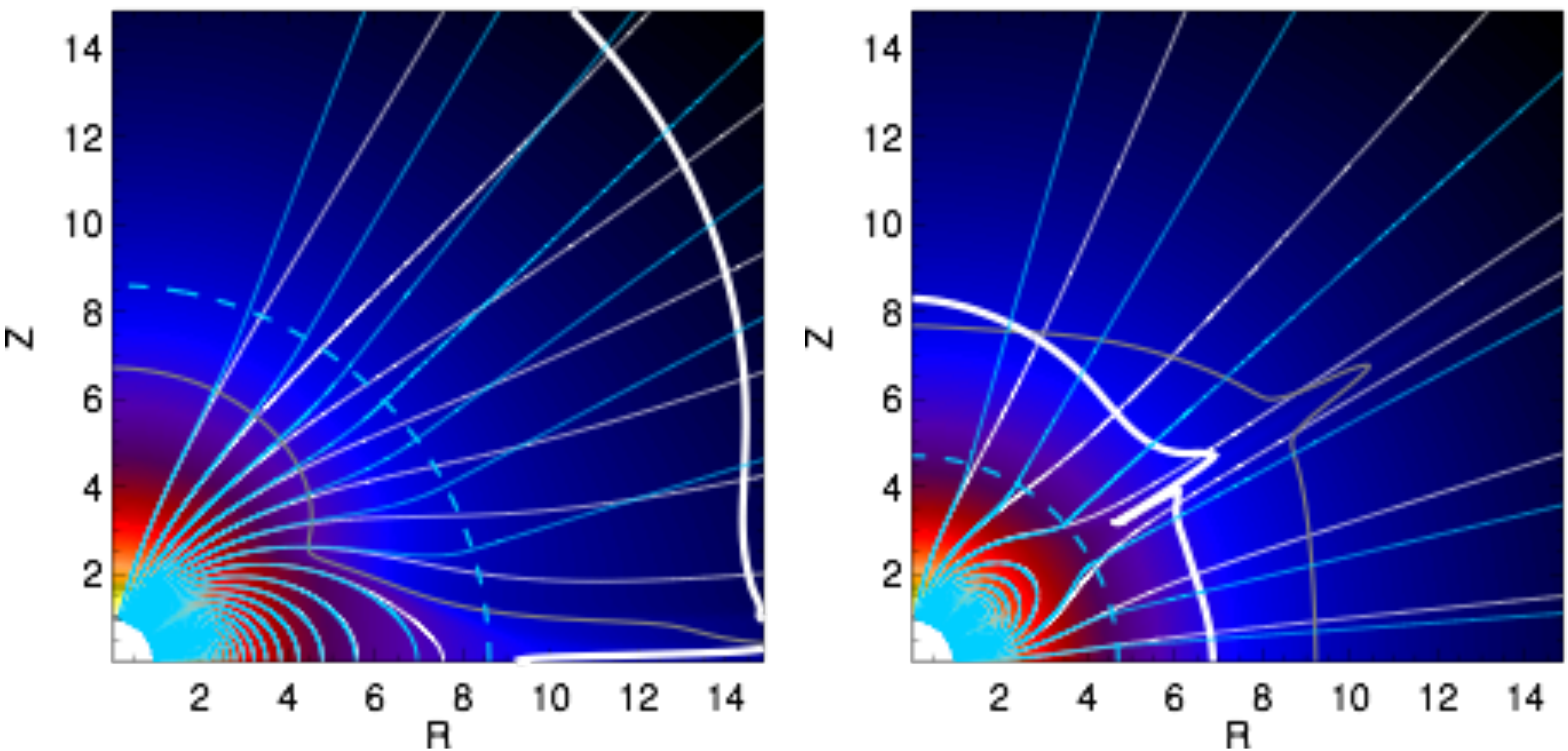
Which value for Rss ?

Definition of an « optimal » source surface radius:

Zero of:

$$||\Phi_{open,simu} - \Phi_{open,potex}(R_{ss})||$$

Rss varies with period, magnetic field strength and topology

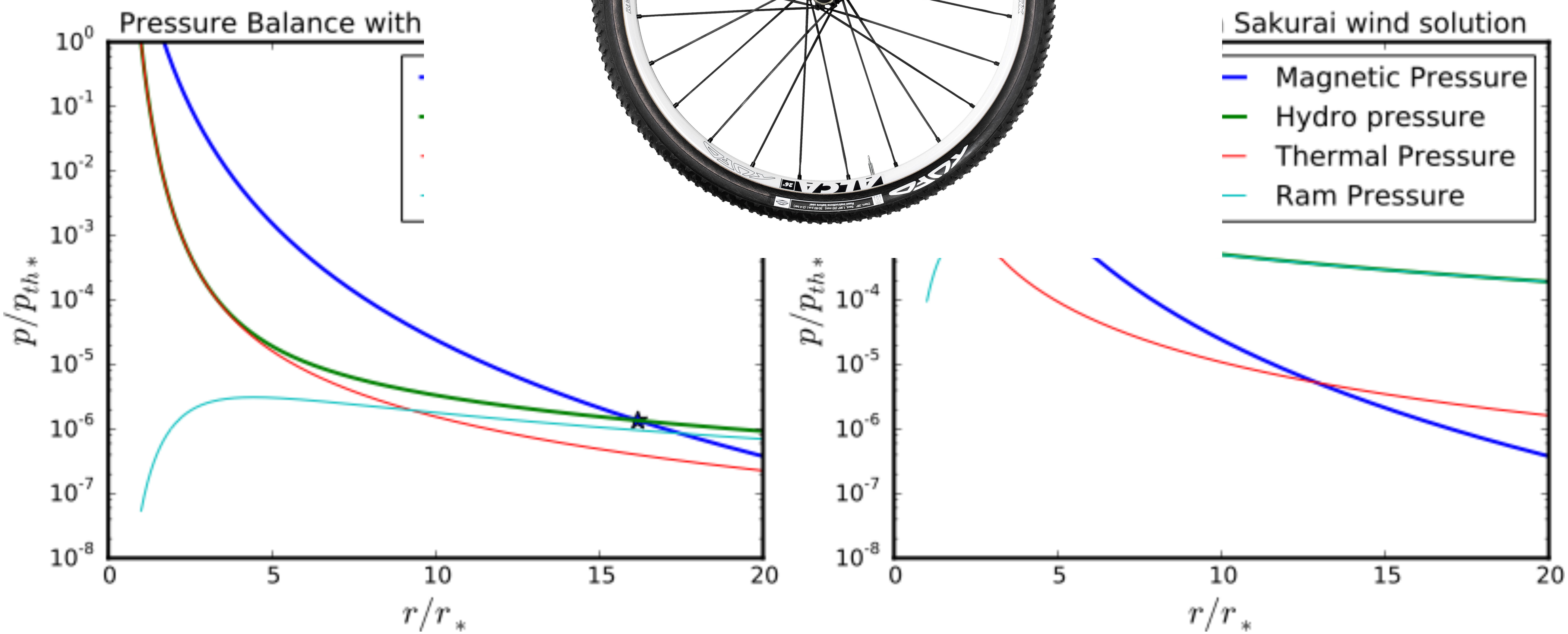


Prediction of Rss

Two wind mode *trifugal effect*

P_{th}

Sakurai 1985



Réville, Brun et al. submitted to ApJ

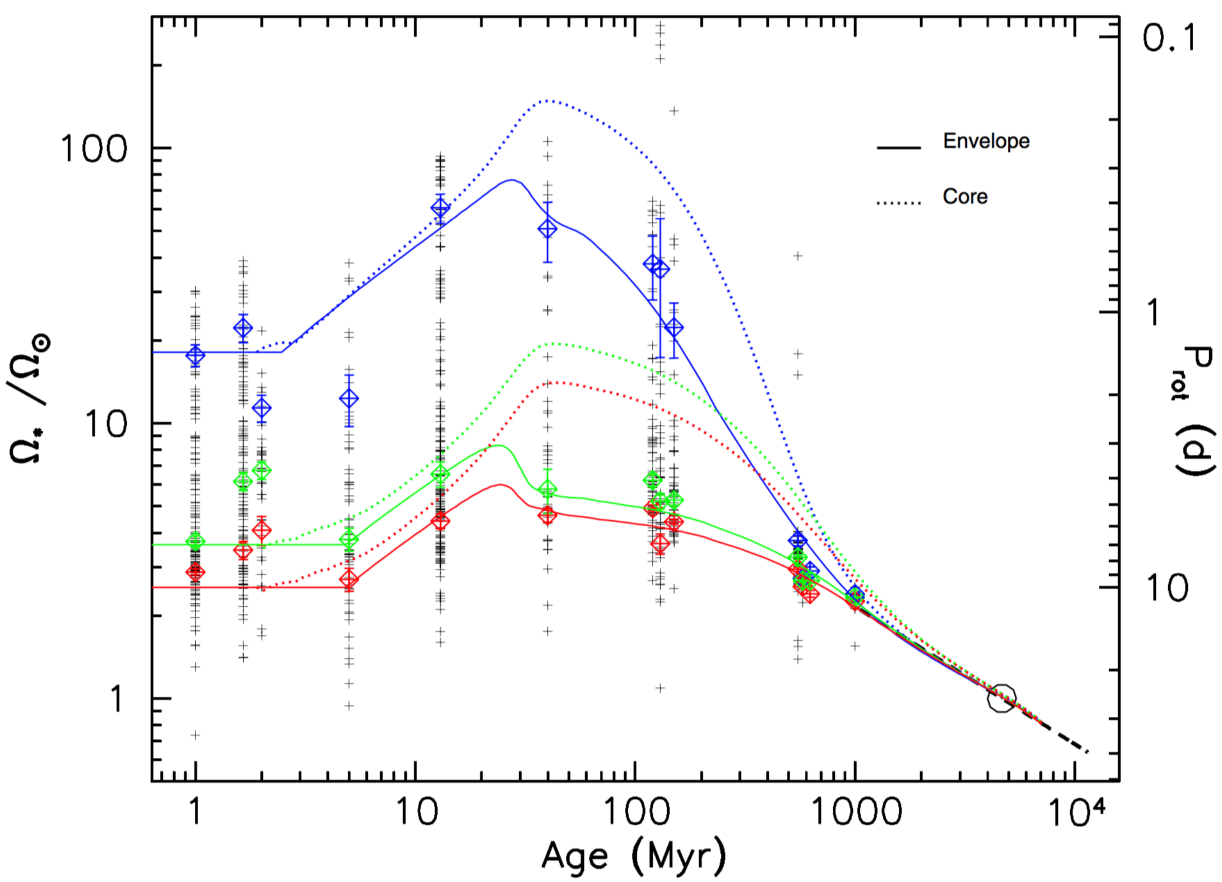
The Sakurai wind solution is obtained through a 6D Newton-Raphson Method

What now ?

Constraining stellar parameters !

Torque is well known !

Gallet & Bouvier 2013



Unknowns:

Coronal temperature
Coronal Density
Mass loss rate

$$n_0 = n_{0,\odot} \left(\frac{\Omega}{\Omega_\odot} \right)^{n_n} \qquad T_0 = T_{0,\odot} \left(\frac{\Omega}{\Omega_\odot} \right)^{n_T}$$

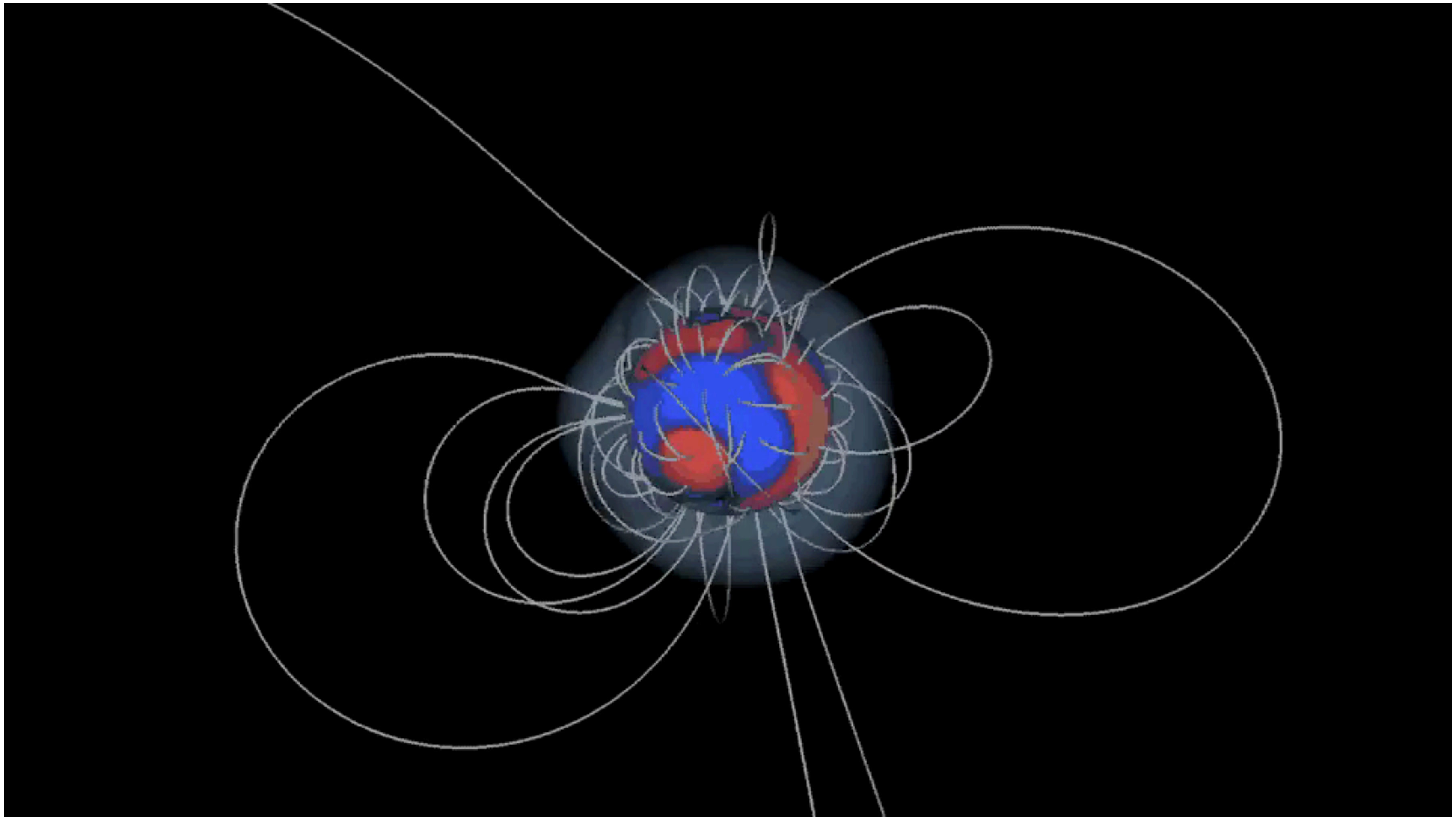
$$B_0 = B_{0,\odot} \left(\frac{M}{M_\odot} \right)^{-1.6} \left(\frac{\Omega}{\Omega_\odot} \right)^{n_\Phi}$$

Holzwarth & Jardine 2007

3D Simulations of a aging K-Star

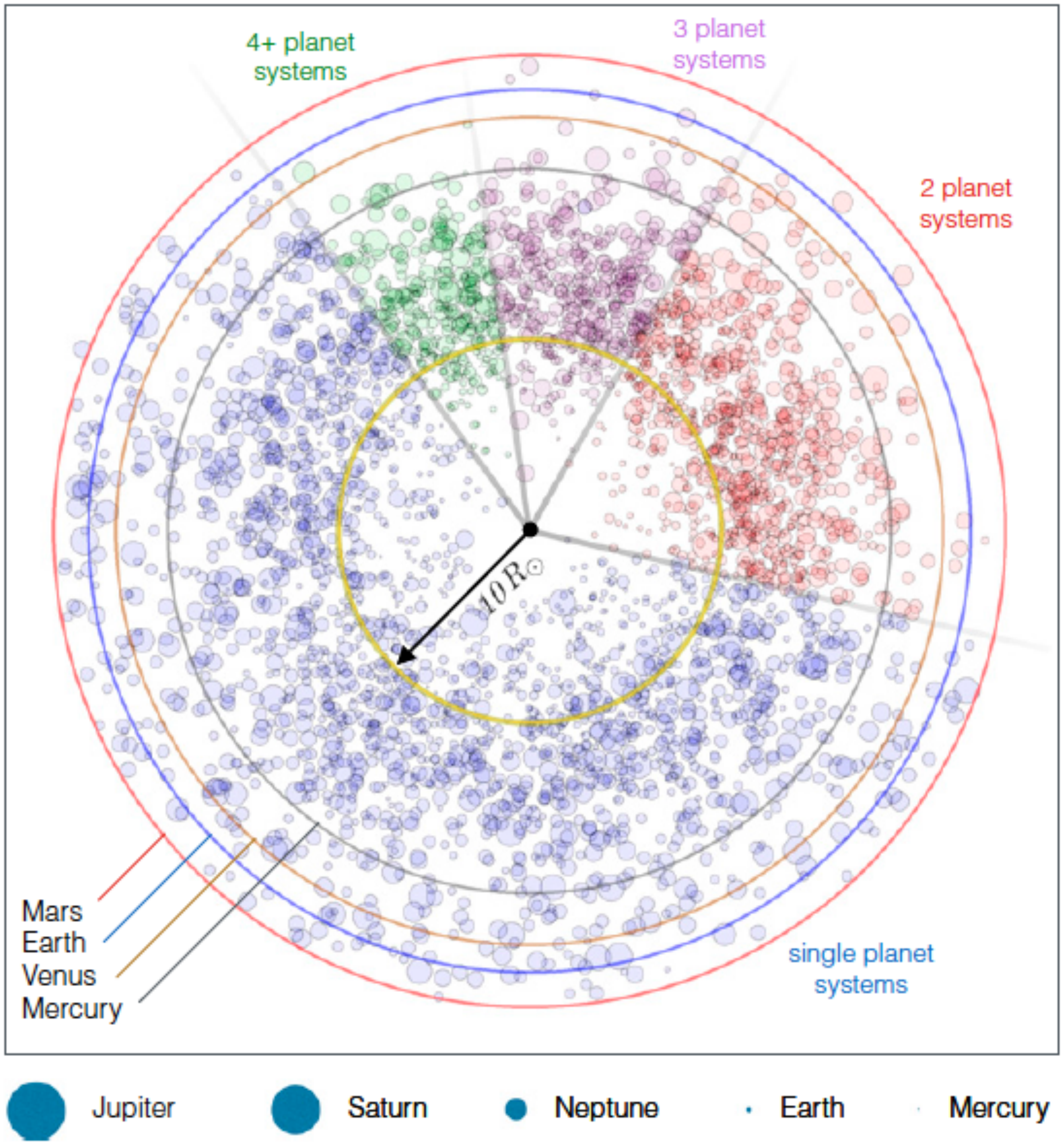
- BD-16351	27	Myr
- TYC-5164-567	120	Myr
- DX Leo	257	Myr
- AV 2177	584	Myr
- HD 190771	2.7	Gyr
- HD 146233	4.7	Gyr
- HD 3751	8	Gyr

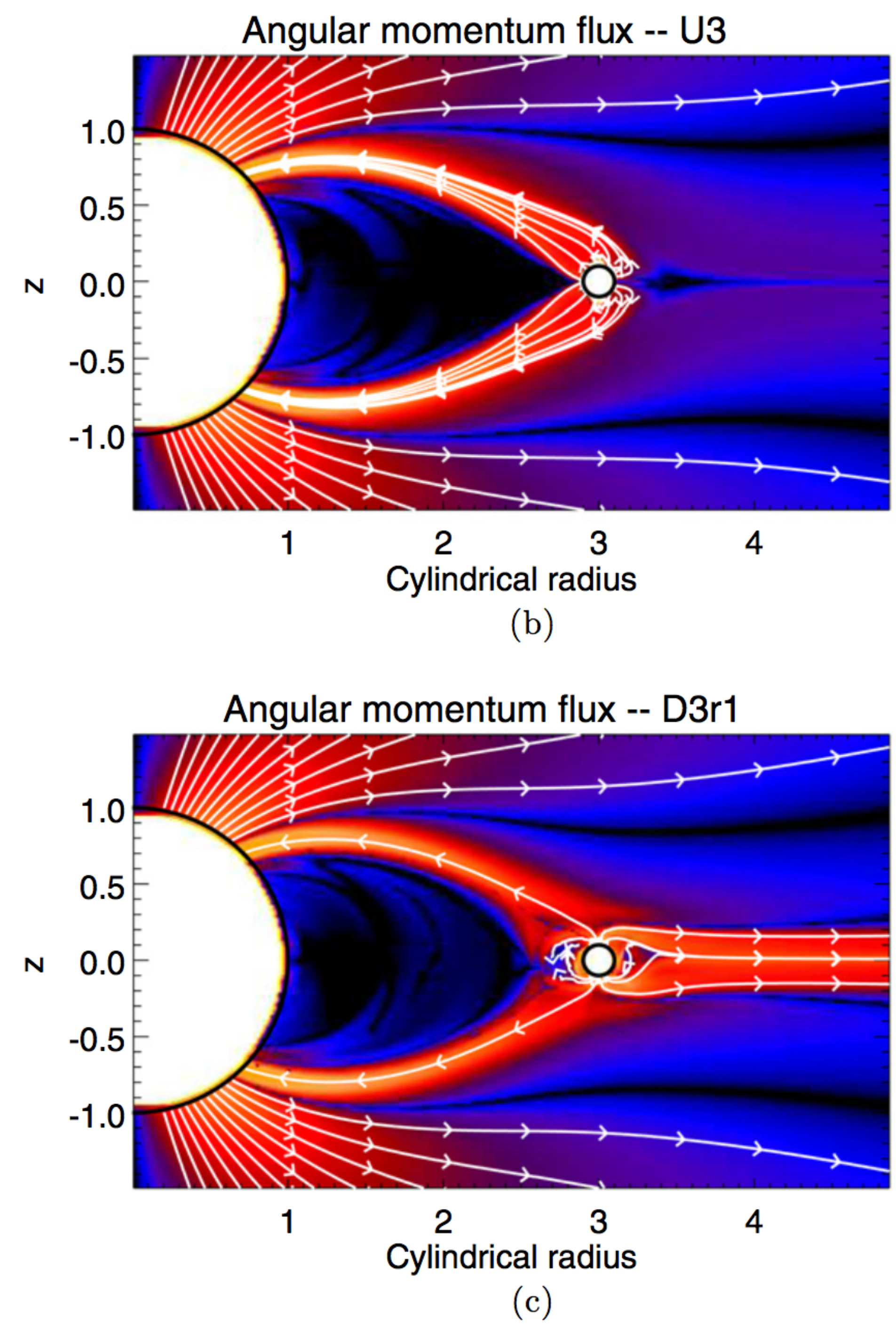
TOUPIES
TOwards Understanding the sPIn Evolution of Stars



HD 190771

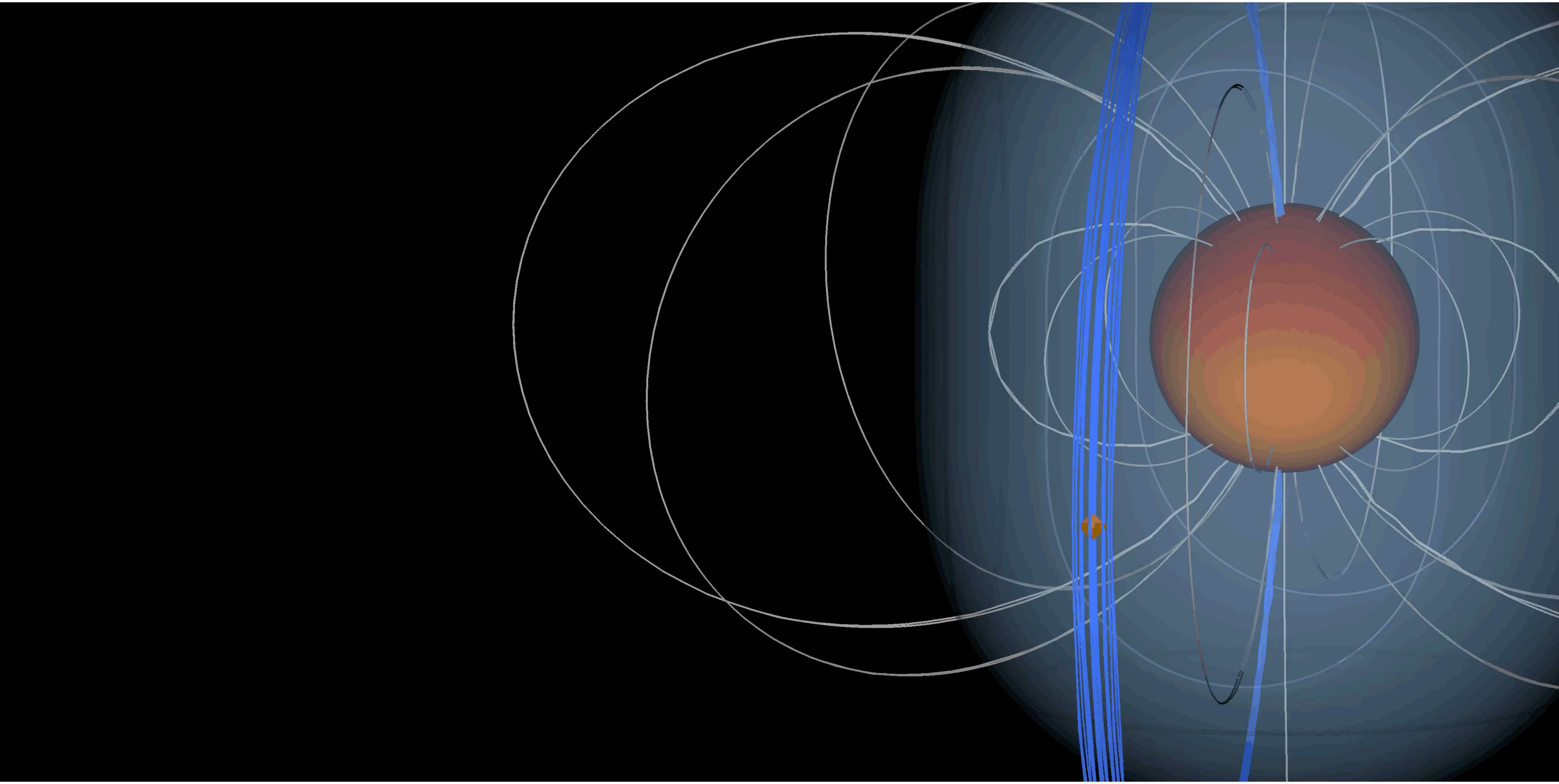
What about exoplanets ?





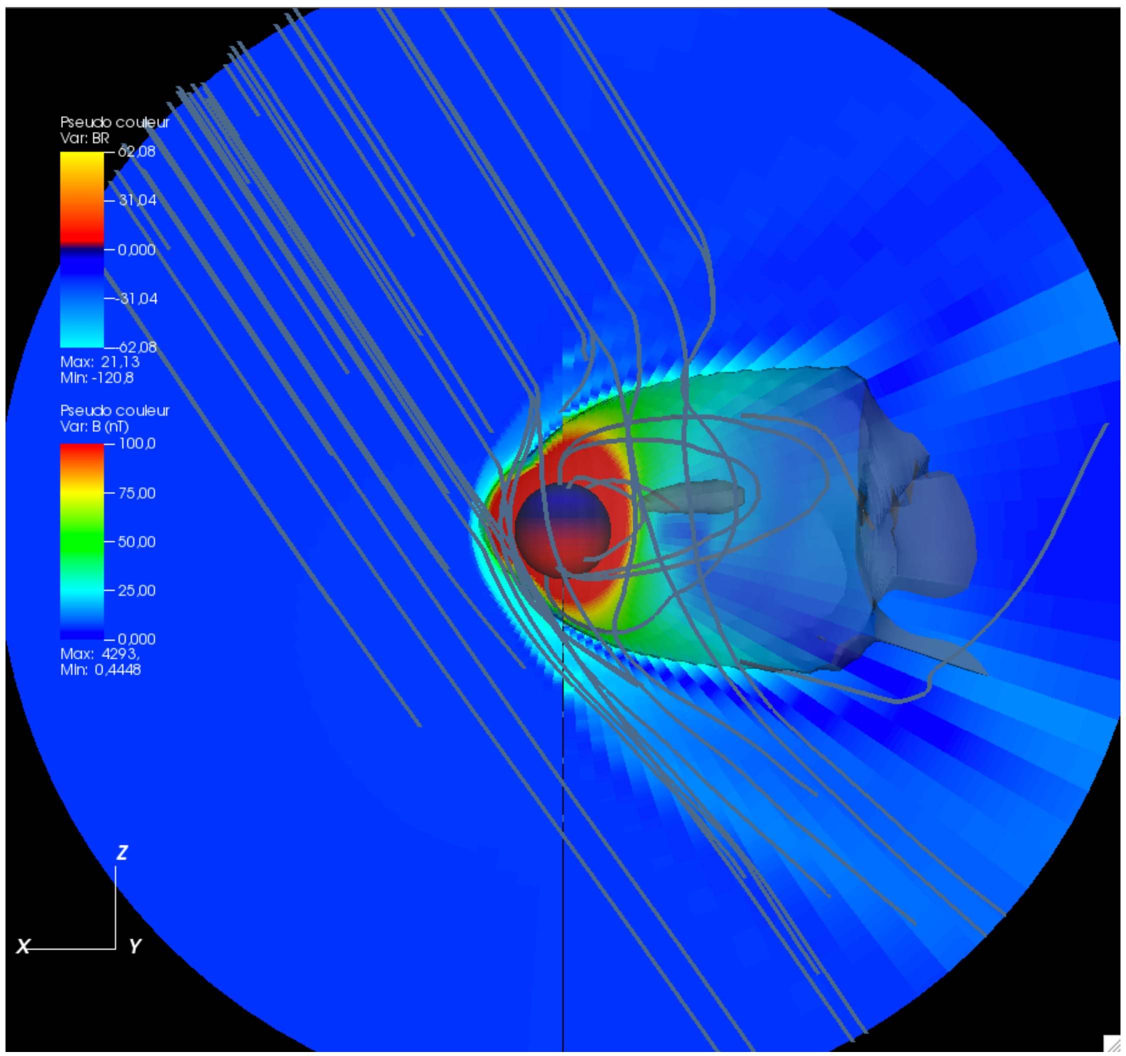
Strugarek, Brun, Matt, Réville, 2014, Apj 795

What about exoplanets ?



3D Wind Planet Interactions

Local setup centered on the planet

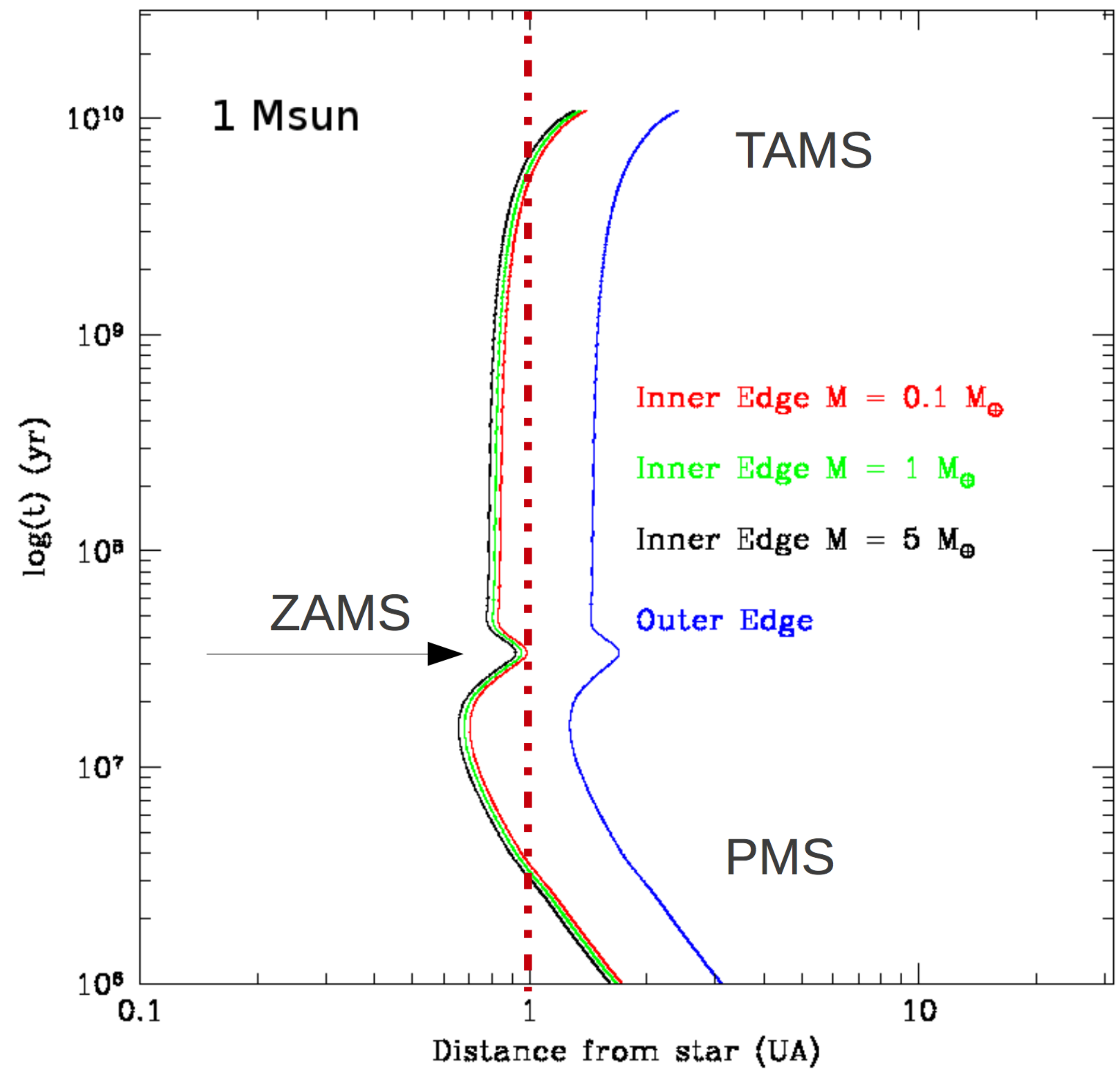


Time varying boundary conditions

+

Cyclotron-Maser emission at wind/magnetosphere interface

Habitable Zone vs Age



A. Palacios, L. Amard ®

Articles and Conference Proceedings

Articles :

1) The Effect of Magnetic Topology on Thermally Driven Wind: Toward a General Formulation of the Braking Law, Réville, V., Brun, A.S., Matt, S., Strugarek, A., Pinto, R., ApJ, 798, 166

2) *On the Diversity of Magnetic Interactions in Close-in Star-Planet Systems,* Strugarek, A., Brun, A.S., Matt, S., Réville, V., ApJ, 795, 86

3) *A concept mission consisting of six spacecraft in a heliocentric orbit at 0.72 AU*, Ritter, B., Meskers, A. J. H., Miles, O., Rußwurm, M., Scully, S., Roldán, A., Hartkorn, O., Jüstel, P., Réville, V., Lupu, S., Ruffenach, A.

4) *From Solar to Stellar Corona: The Role of Wind, Rotation and Magnetism*, Réville, V., Brun, A.S., Strugarek, A., Matt, S., Bouvier, J., Folsom, C.P., Petit, P. *Submitted to ApJ*

Proceedings :

1) The influence of the magnetic topology on the wind braking of sun-like stars.

Réville, V., Brun, A.S., Matt, S., Strugarek, A., Pinto, R., Compte-rendu des journées SF2A 2014, pp. 509-513

2) Modelling the Corona of HD 189733 in 3D

Strugarek, A., Brun, A.S., Matt, S., Réville, V., Donati, J.F., Moutou, C., Fares, R. Compte-rendu des journées SF2A 2014, pp. 279-284

3) Numerical aspects of 3D stellar winds

Strugarek, A., Brun, A.S., Matt, S., Réville, V., Compte-rendu du Cool Stars Cambridge Workshop n°18

4) Cool Stars and Space Weather

Vidotto, A.A., Jardine, M., Cameron, A.,C., Morin, J., Villadsen, J., Saar, S., Alvarado, J., Cohen, O., Holzwarth, V., Poppenhaeger, K., V. Réville, V.

Compte-rendu du Cool Stars Cambridge Workshop n°18

5) Modeling magnetized star-planet interactions: boundary conditions effects

Strugarek, A., Brun, A.S., Matt, S., Réville, V., Compte-rendu IAU Symposium 300 (2013), pp. 330-334, Thanks for your attention !