Dynamical Evolution of Stars
Sun in time and solar/stellar wind

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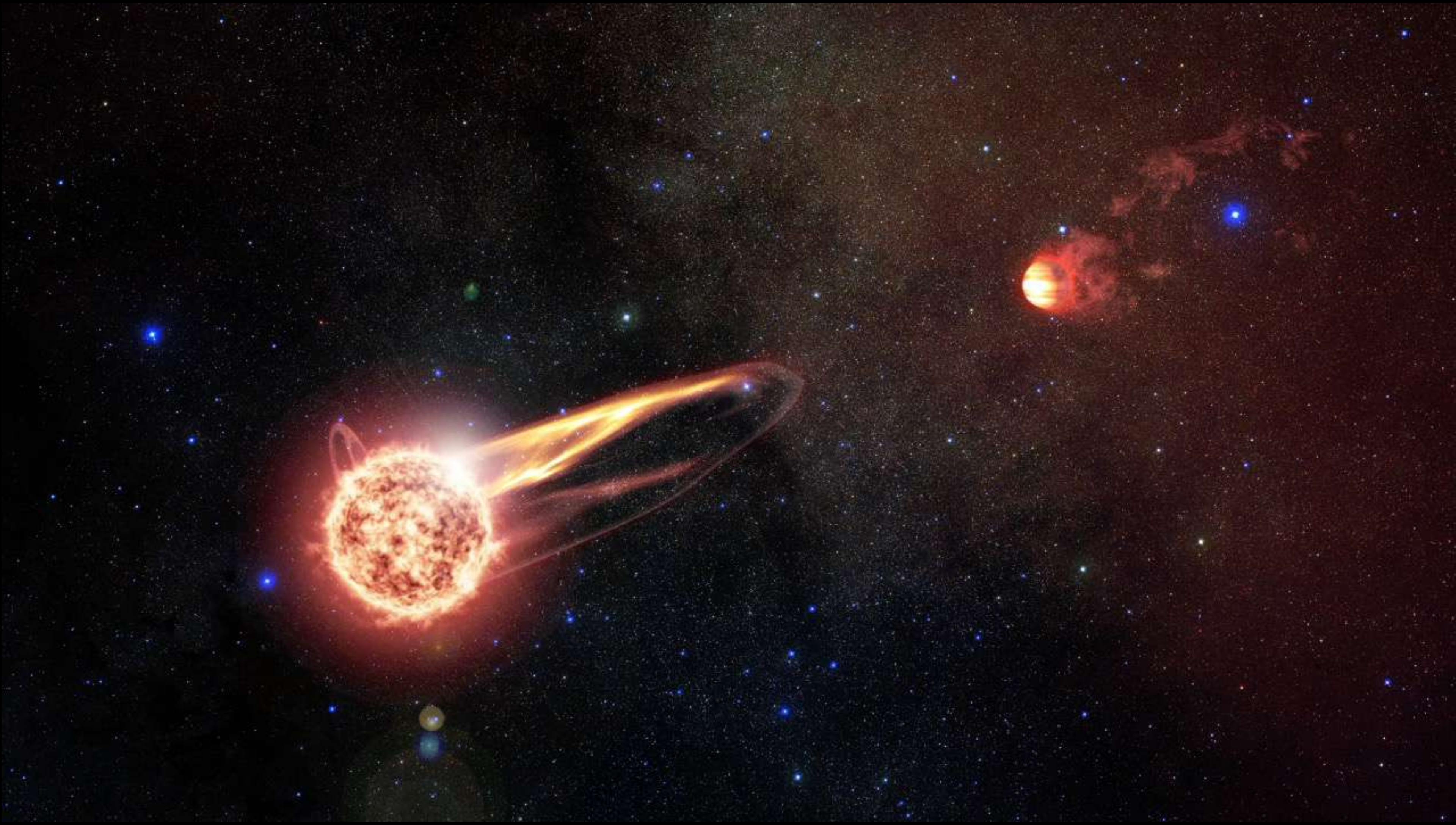
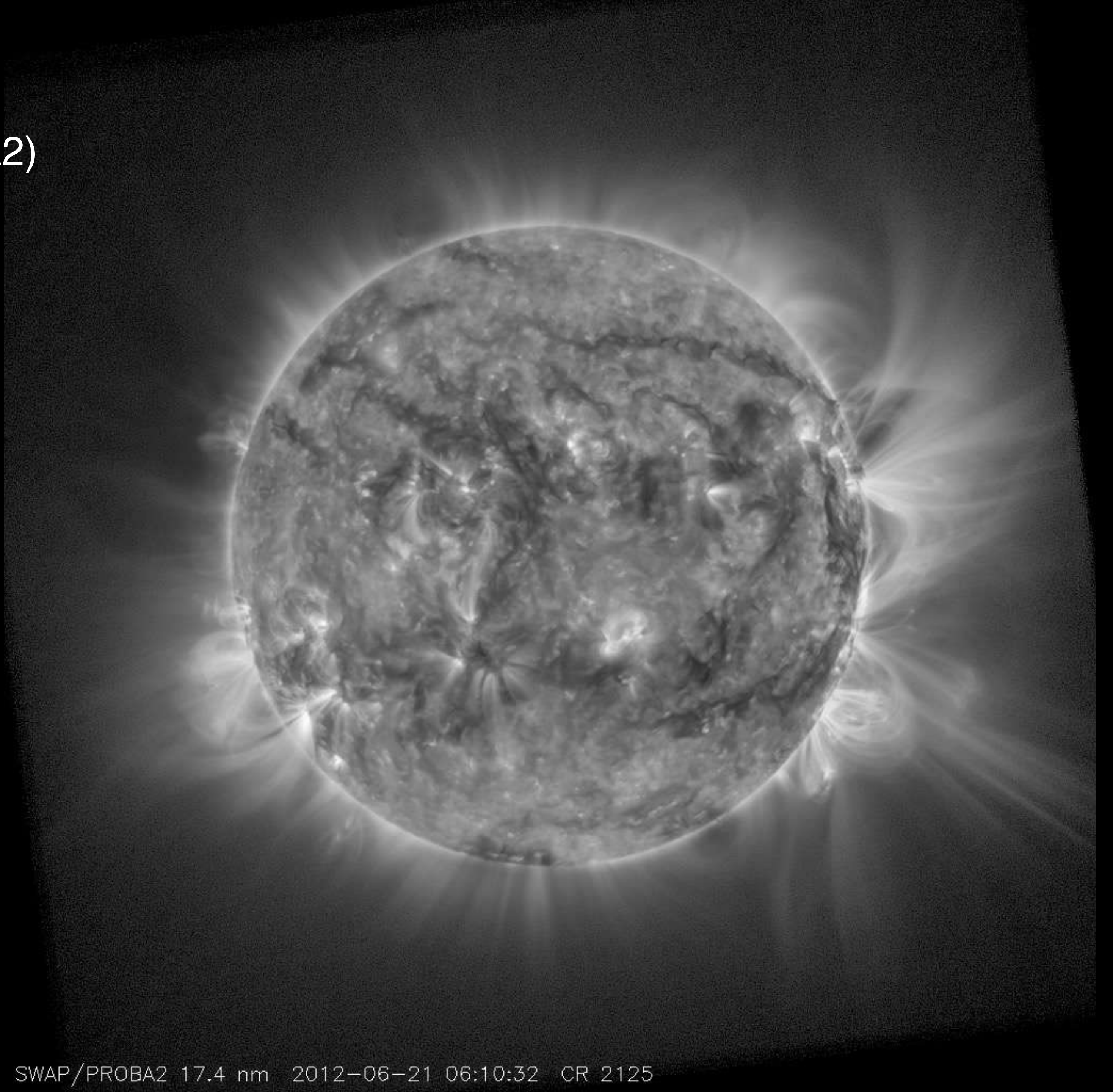
Exo Space Weather: What are we talking about?

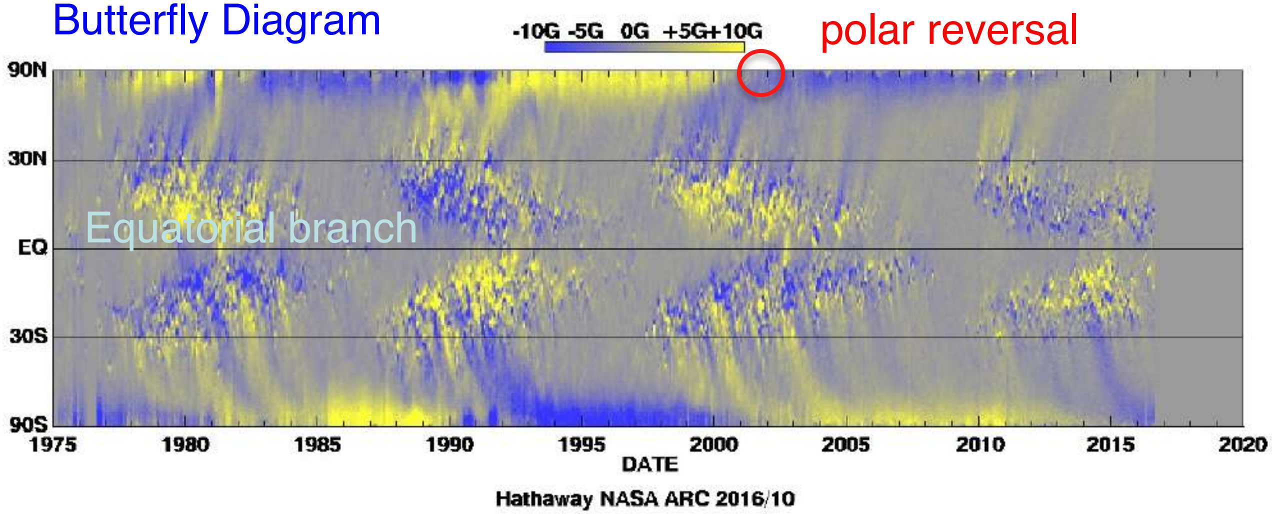


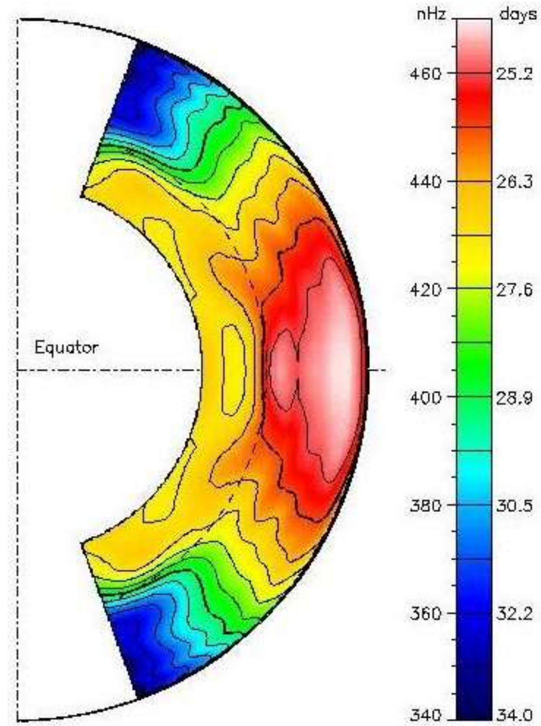
Sun in UV
(ESA/Proba2)



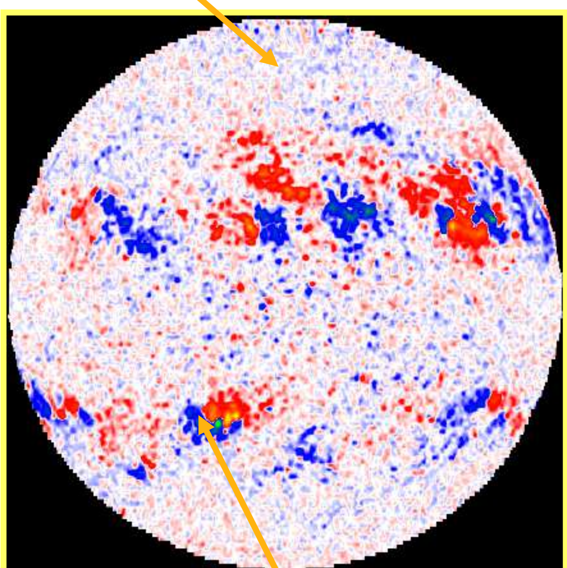
Solar Cycle and Flows

Butterfly Diagram



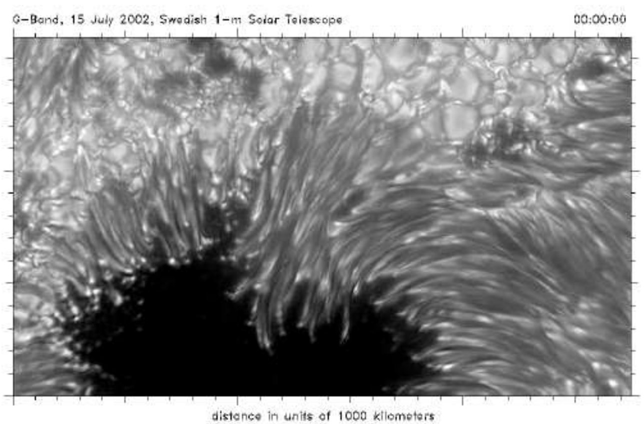


Quiet

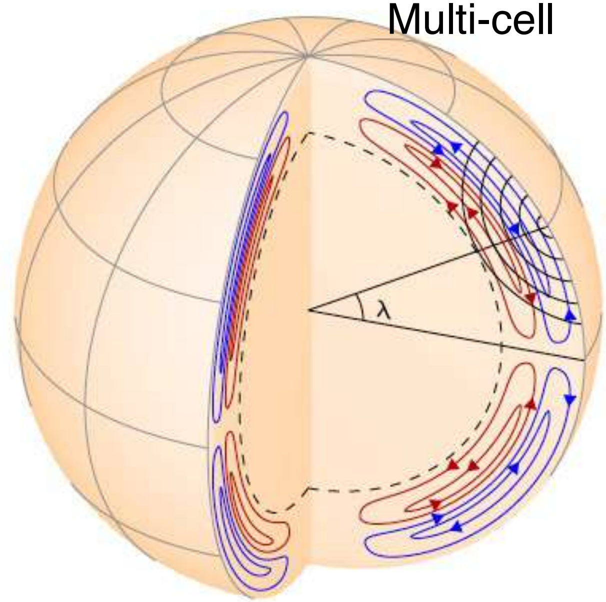


Active

Small vs Large Scale Dynamos

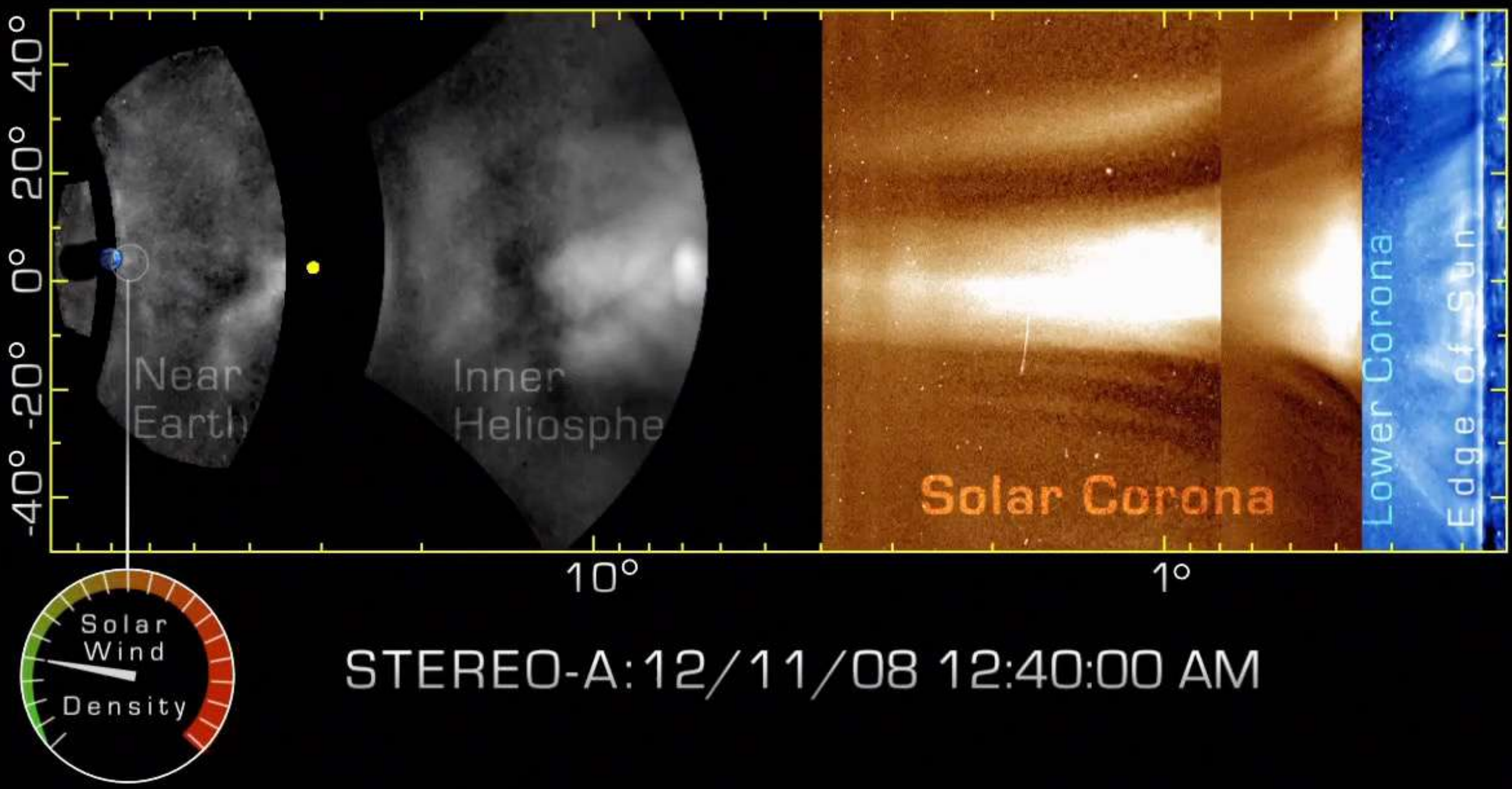


Multi-cell



Zhao et al. 2013

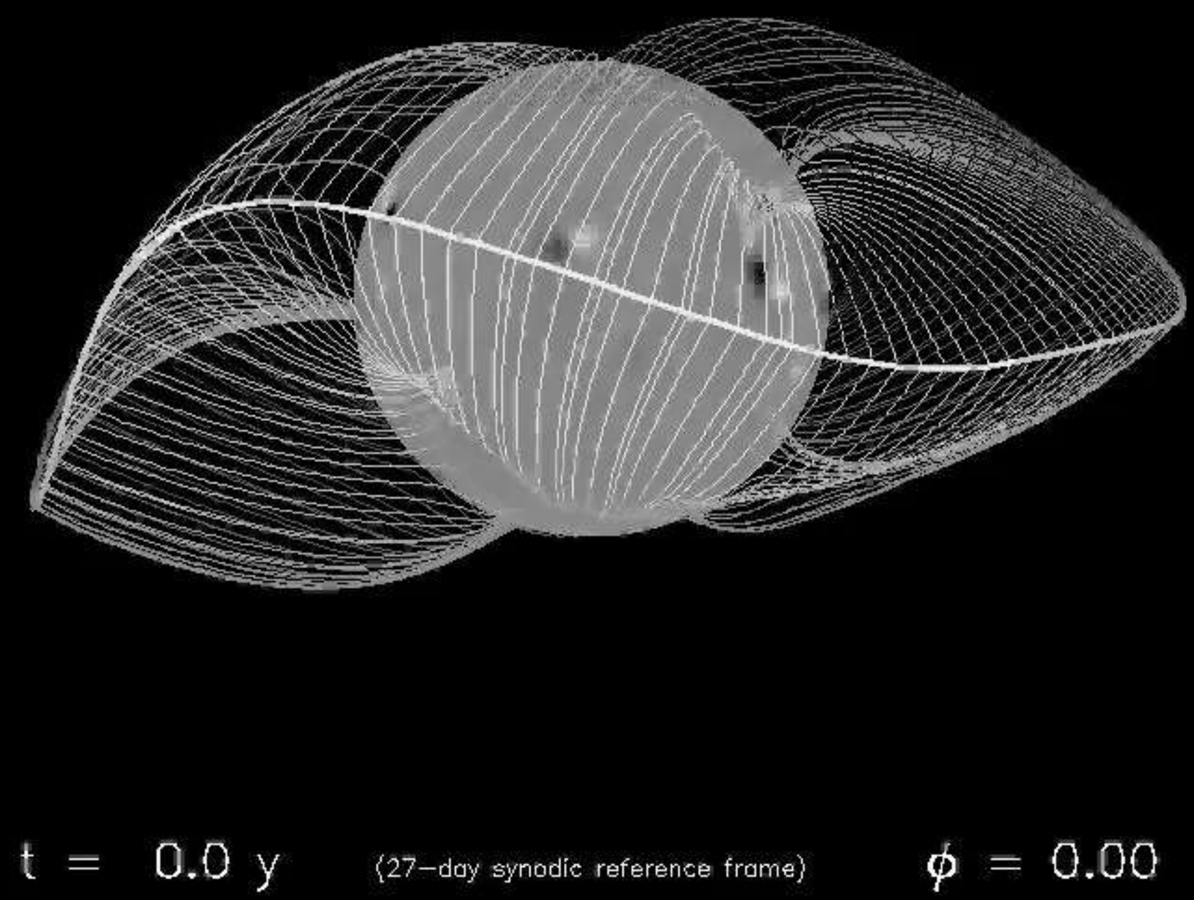
Solar Wind and the Earth



Courtesy: Craig de Forest (SwRI)

The sun: a complex temporal evolution as well…

credit M. De Rosa



Solar-Stellar Connection: observations and models

Solar Type Stars (late F, G and early K-type)

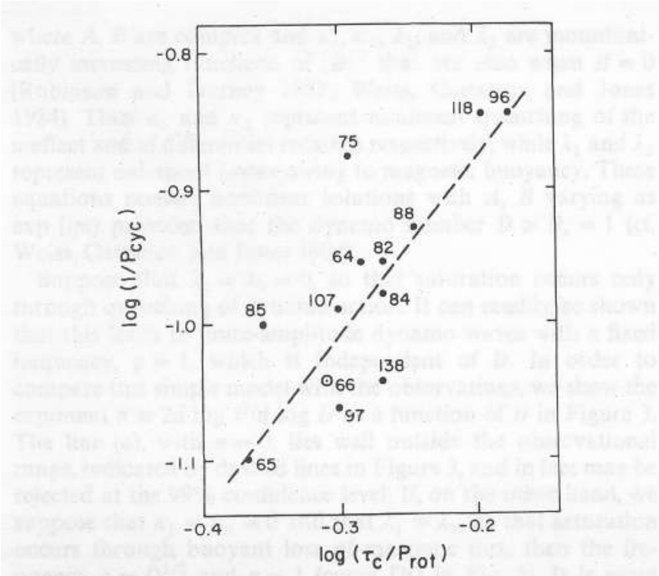
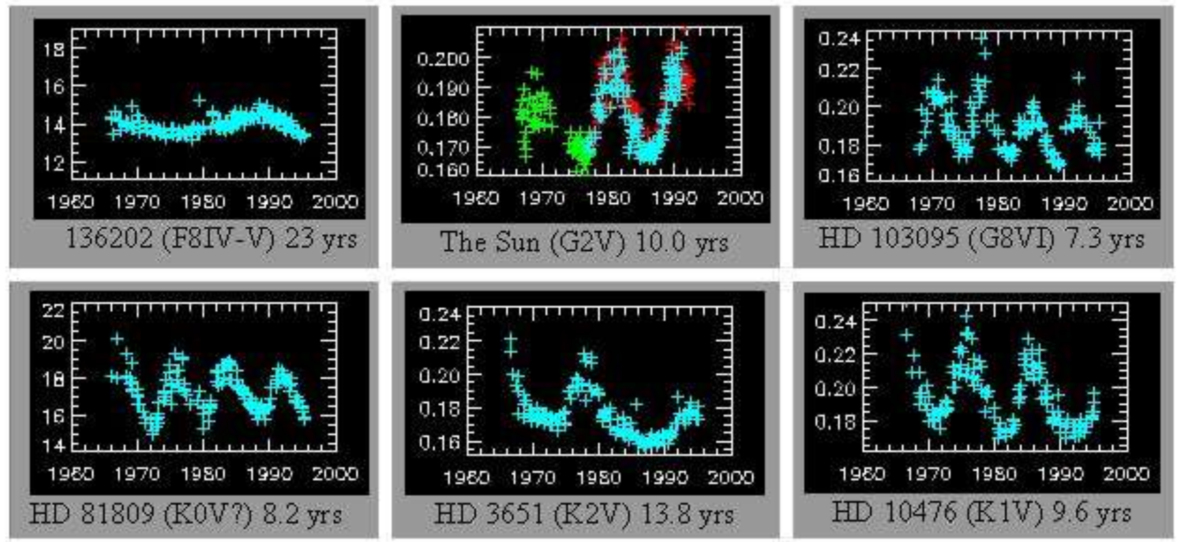


FIG. 2.—Log $(1/P_{cyc})$ vs. log (τ_c/P_{rot}) for the stars of Table 1. The dashed line is a linear least squares fit to the data.

Noyes et al. 1984



In stars activity depends on rotation & convective overturning time via Rossby nb $Ro=P_{rot}/\tau$

$<R'_{HK}> = Ro^{-1}$, $P_{cyc}=P_{rot}^{1.25+/-0.5}$

Wilson 1978

Baliunas et al. 1995

CaII H & K lines , $<R'_{HK}>$

Over 111 stars in HK project (F2-M2):

31 flat or linear signal

29 irregular variables

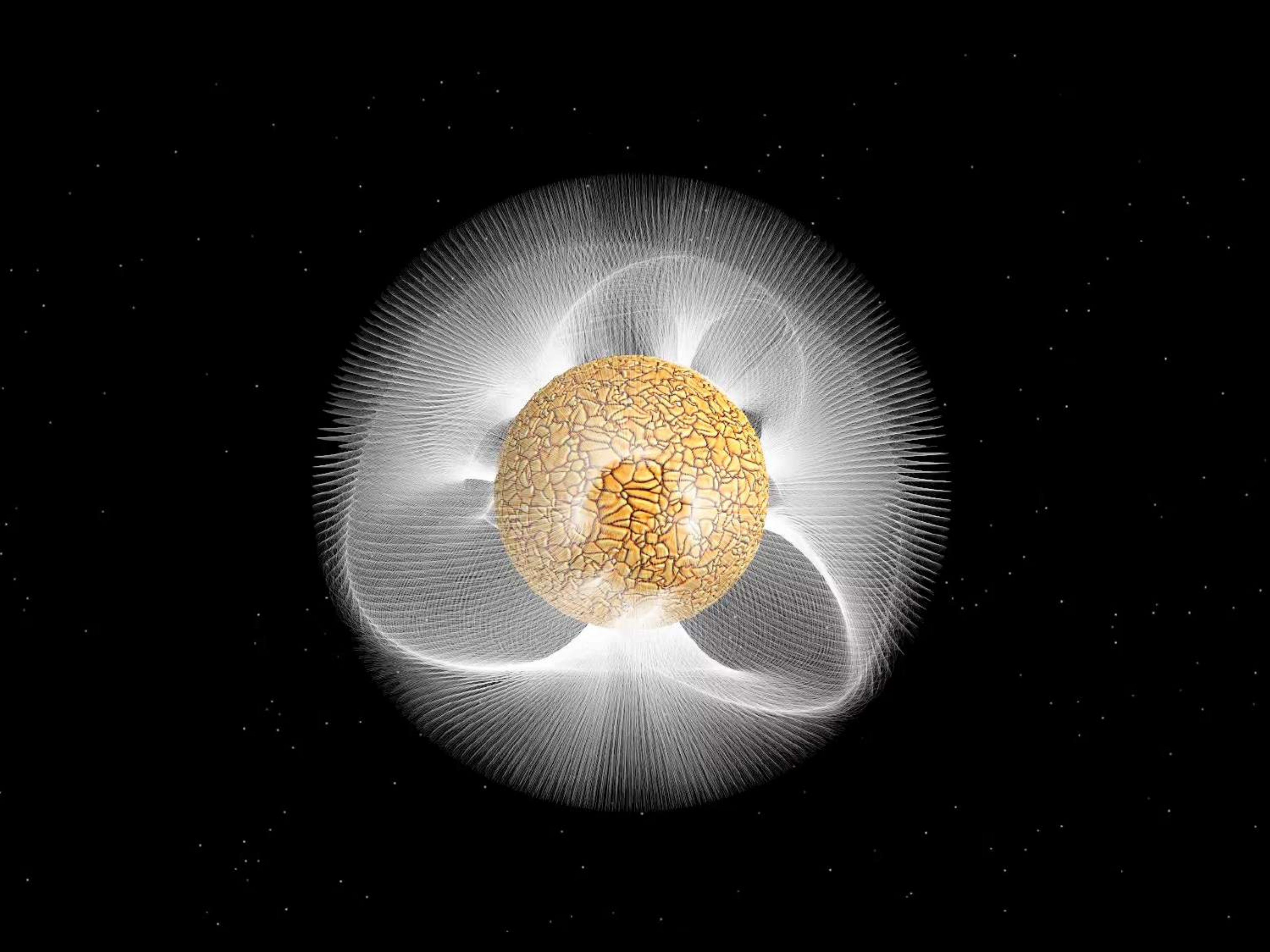
51 + Sun possess magnetic cycle

=> Much more coming in Asteroseismology Era (Mike's talk)

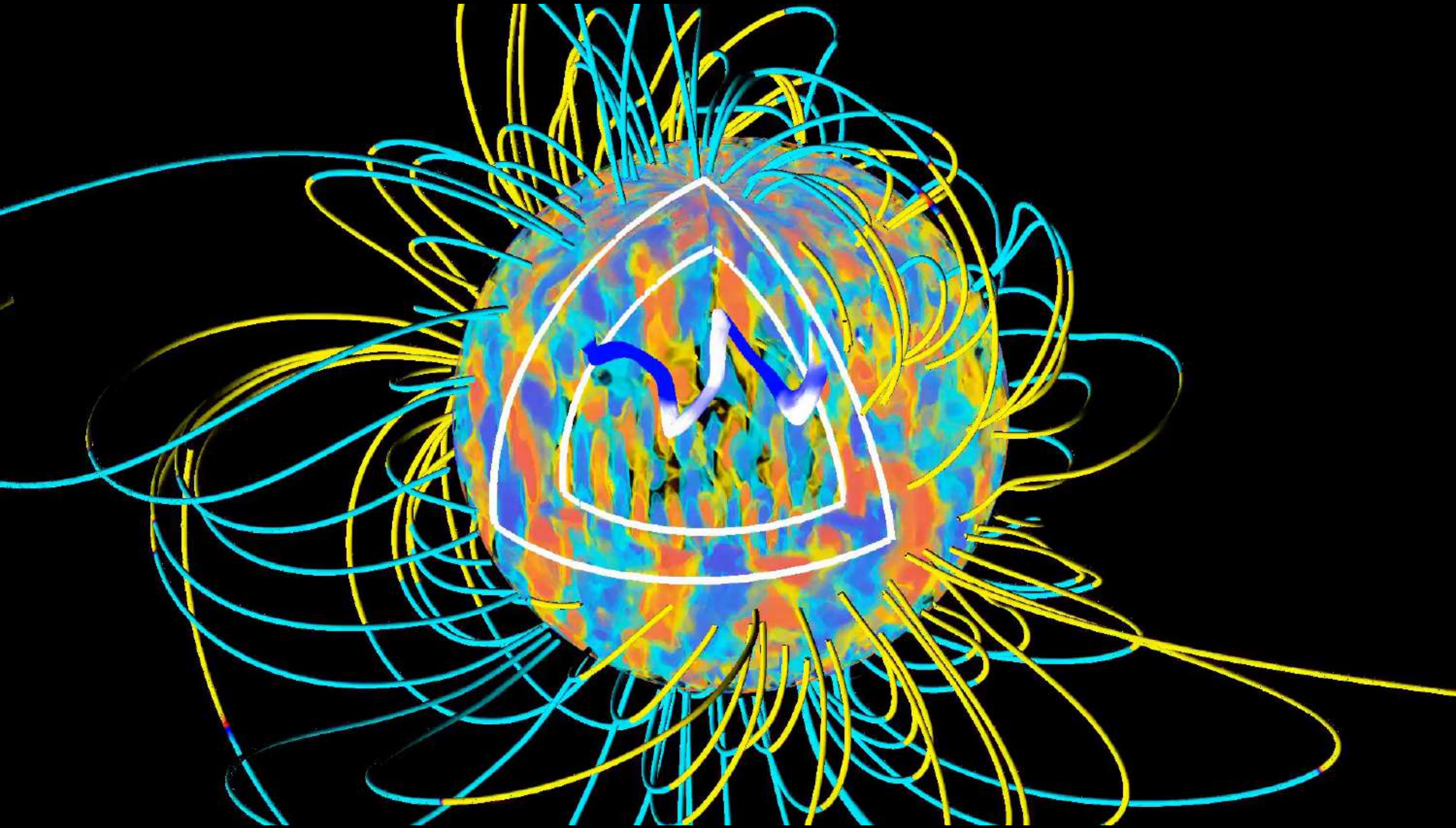
Quid of Star-Planet Interaction and cyclic activity?

Magnetic cycles of the planet-hosting star τ Bootis

J.-F. Donati,[1★] C. Moutou,[2★] R. Farès,[1★] D. Bohlender,[3★] C. Catala,[4★] M. Deleuil,[2★] E. Shkolnik,[5★] A. C. Cameron,[6★] M. M. Jardine[6★] and G. A. H. Walker[7★]

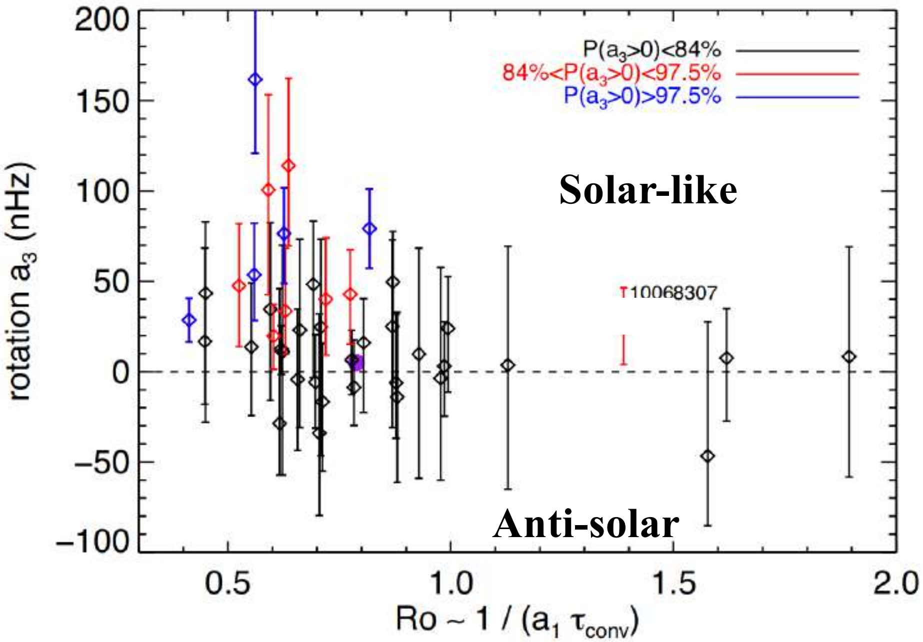


Cyclic Nonlinear Stellar Dynamo



Solar-like star Differential Rotation

Benomar+ 17;
see also Reinhold & Gizon 15

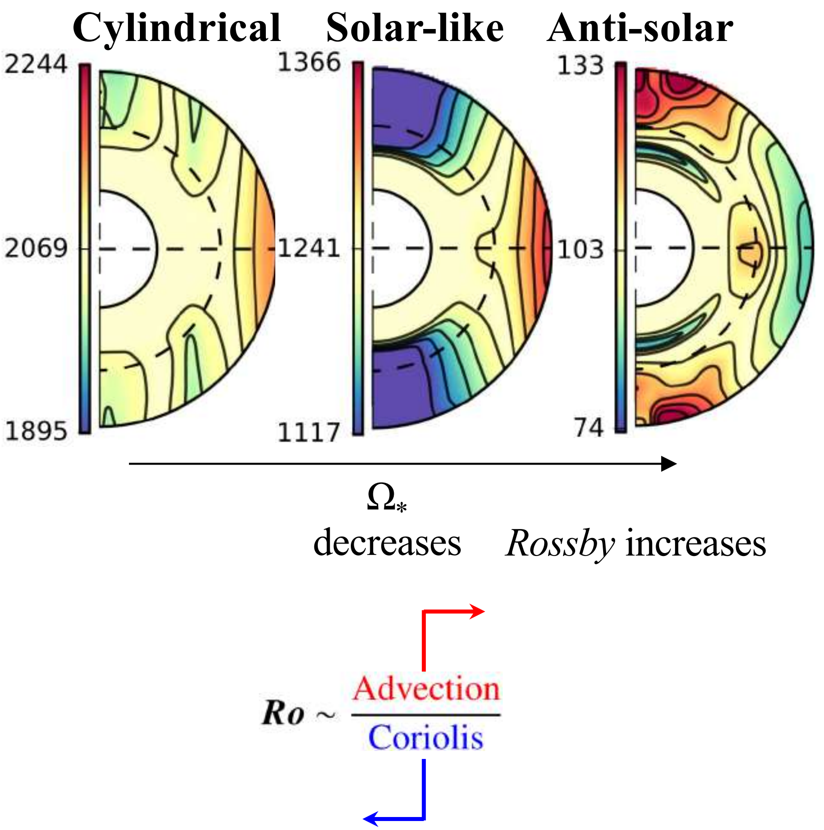


fast rotators slow rotators

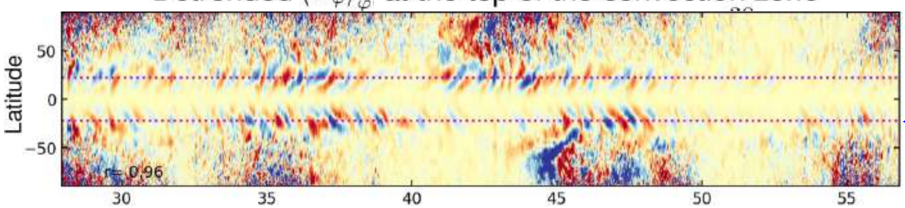
- Precision decreases for slow rotators

- Different DR profiles are found in numerical simulations:

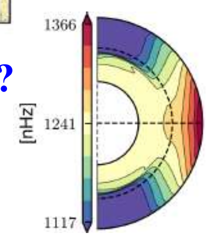
Brun+ 17 ;
see also Gilman 75,77; Kapyla+ 11; Guerrero+ 13, Gastine +14

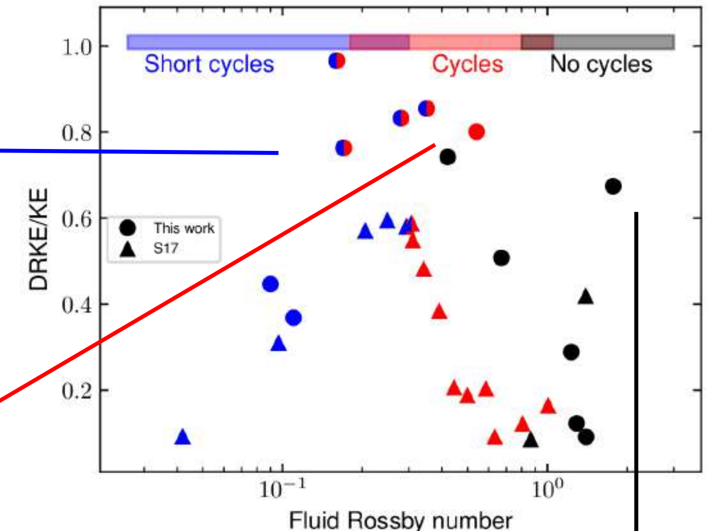


Detrended $\langle B_\varphi \rangle_\varphi$ at the top of the convection zone

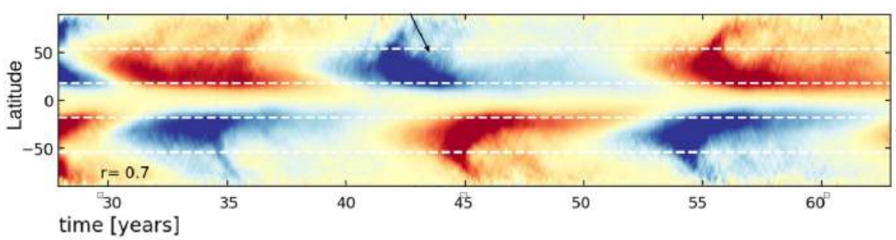


Brun, Strugarek, Noraz+ 22





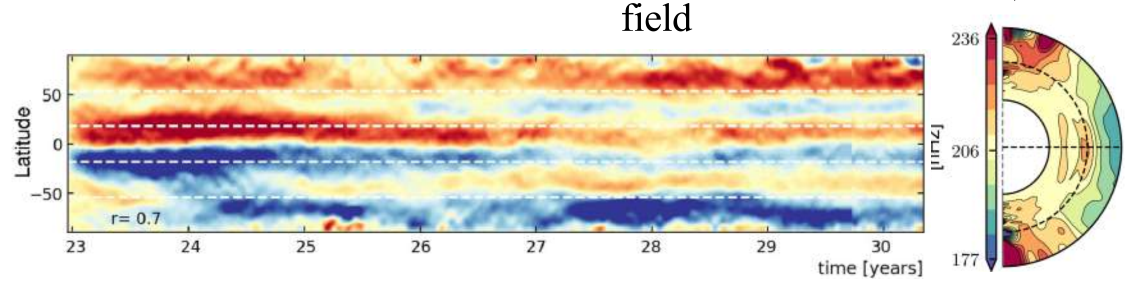
- short cycles (~year) ; **quasi-biennial oscillations ?**
- surface dynamo
- Parker-Yoshimura type (αΩ)



$\langle B_\varphi \rangle_\varphi$ at the base of the convection zone

- **Stationnay** dynamo
- hemispherical toroidal field

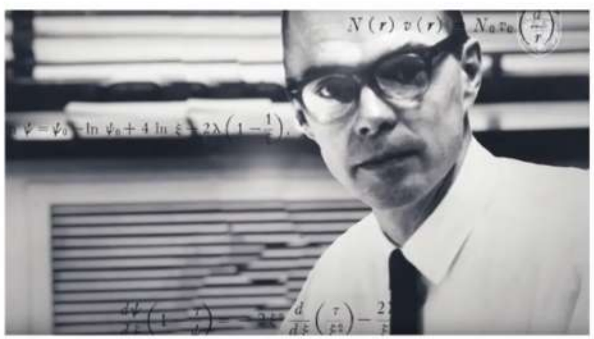
- long cycles (**decadal solar-like**)
- deeper dynamo
- non-linear retroaction



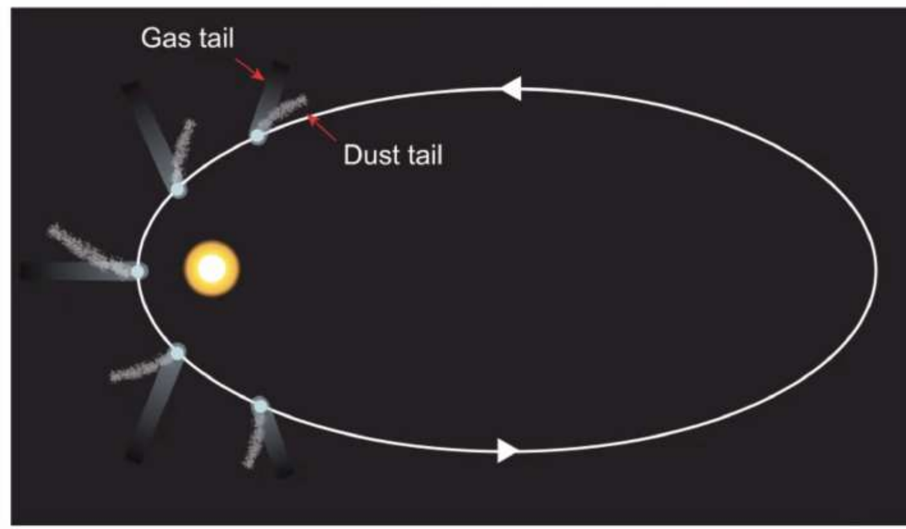
Stellar Wind and Complex Topologies

Comet Tails

Ludwig Biermann

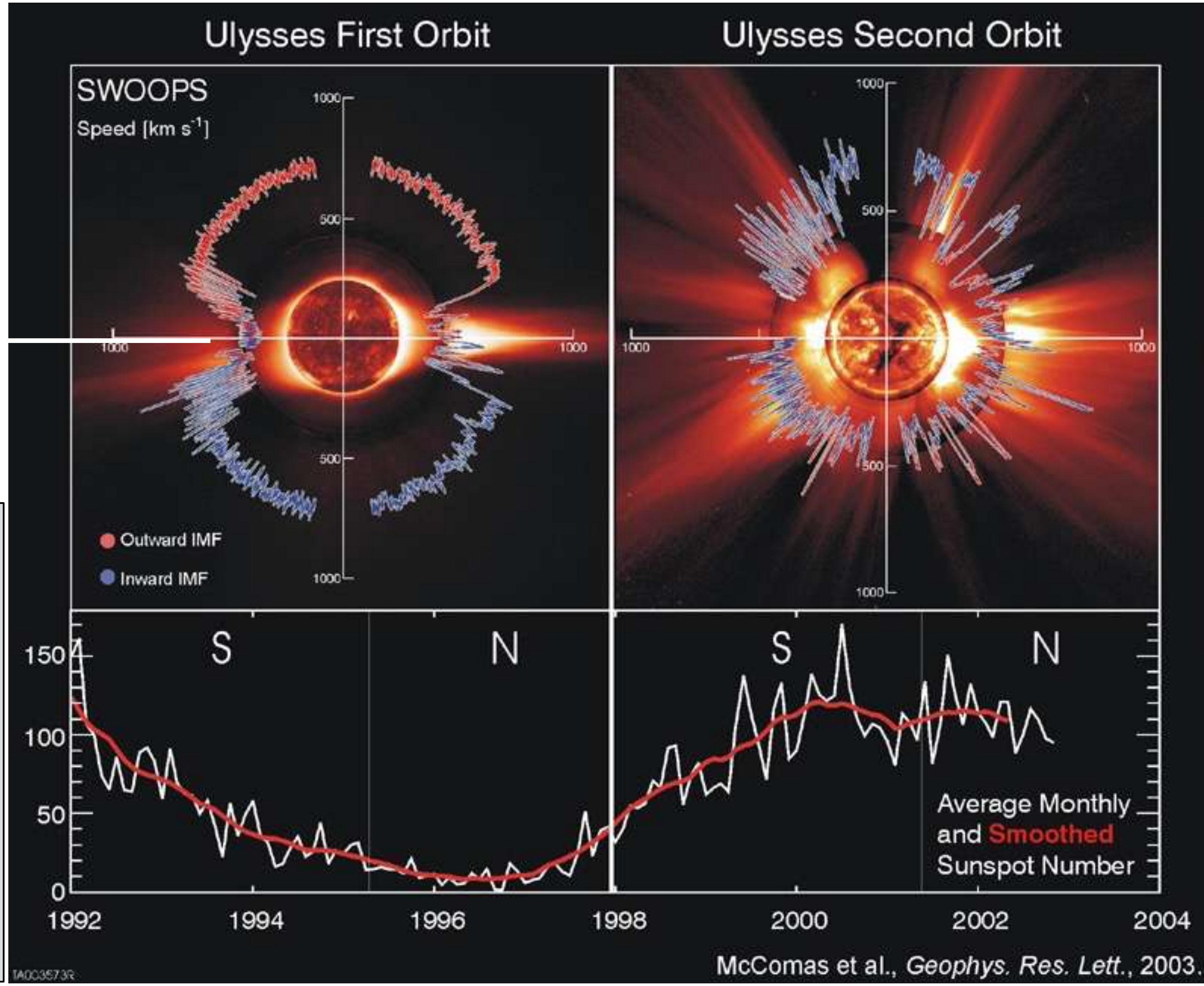


Eugene Parker



Gaz/ion tail proof of the existence of a flow of particles (e.g. wind)

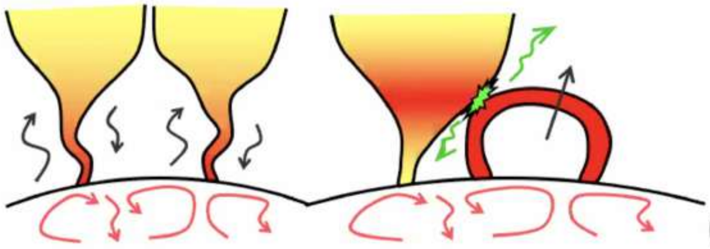
Solar wind and coronal magnetic field



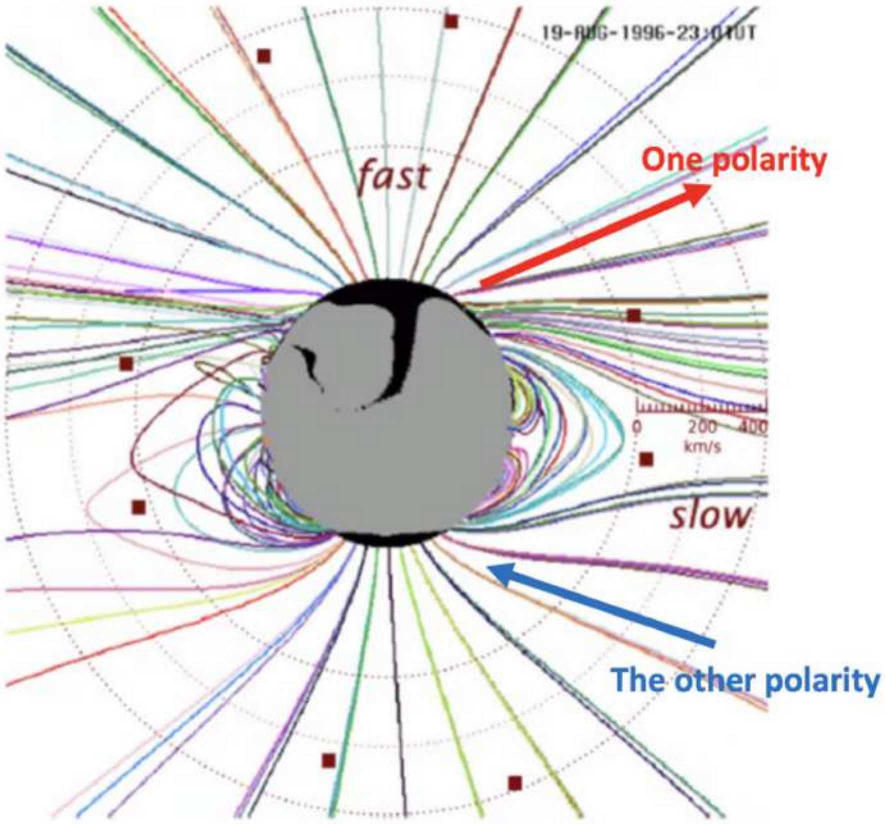
It takes between **2.5 to 4.5 days** for the **solar wind to reach the Earth.**
It is composed in majority **of ionized hydrogen** (protons+e$^-$), **alpha particles** and some trace heavy elements (ions).

Solar wind origins and heating

- Fast solar wind (steady)
  - Emerges from open field lines, mostly over poles, but with equatorial extensions
- Slow solar wind (steady)
  - Escapes intermittently from the streamer belt
    - Reconnection at CH boundary?
    - Reconnection at streamer tips?
    - KH instability?
    - Small CHs and overexpansion?
- Heating mechanisms:
- waves/turbulence
- reconnection



(Cranmer cartoon)



(Antonucci et al., 2020)

Solar wind parameters at Earth orbit

Table 1 Key average properties of the solar wind plasma near Earth[a]

Quantity	Definition	Source
$B_r = 2.5$ nT	Radial magnetic field	Wang & Neubauer 1990
$B_\varphi = 2.4$ nT	Toroidal magnetic field	Wang & Neubauer 1990
$B_\theta = 1.5$ nT	Latitudinal magnetic field	Wang & Neubauer 1990
$V = 600$ km/s	Solar wind speed	McComas et al. 1998
$\rho = 11 \cdot 10^{-21}$ kg/m^3	Solar wind mass density	Schwenn 1990
$T = 120{,}000$ K	Solar wind temperature	Schwenn 1990
Derived Quantity		
$V_A = 32$ km/s	Alfvén speed	
$C_S = 41$ km/s	Sound speed	
$\beta \sim 1$	Plasma beta	
$\lambda_{mfp} \sim 0.2$–0.5 AU	Mean free path of ion Coulomb collisions	Marsch 1990

[a]These quantities vary near Earth, and also have systematic variability as a function of distance from the Sun.

cea

Solar wind acceleration profiles

'Fast' and 'slow' profiles

Fast wind is relatively uniform

Slow solar wind density is 'blobby'

Minor ions show enhanced acceleration – field-aligned flow

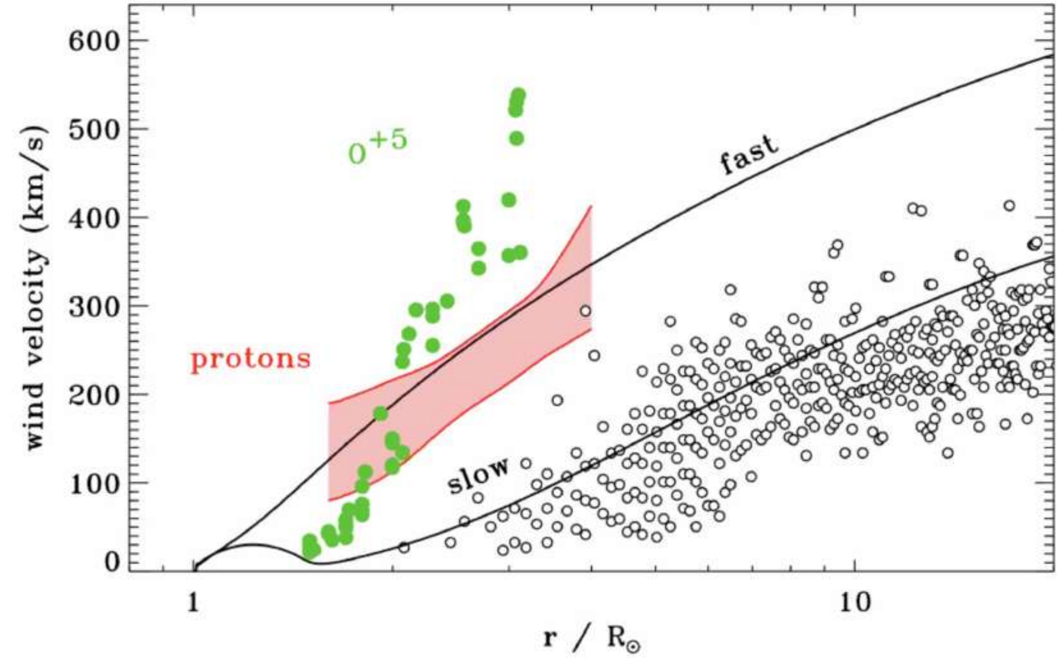


Figure 8: Radial dependence of solar wind outflow speeds. UVCS Doppler dimming determinations for protons (red; Kohl *et al.*, 2006) and O^{+5} ions (green; Cranmer *et al.*, 2008) are shown for polar coronal holes, and are compared with theoretical models of the polar and equatorial solar wind at solar minimum (black curves; Cranmer *et al.*, 2007) and the speeds of "blobs" measured by LASCO above equatorial streamers (open circles; Sheeley Jr *et al.*, 1997).

(Cranmer, 2009)

Parker model for the dynamical solar corona

If one supposes that the solar corona is (hydro)static (u=0) & isothermal (T ~ 1-1.6 MK), the ratio between the solar surface pressure (~ 100 mb) and that " at infinity" gives $P_{inf}/P_{surf} \sim 10^{-4}$. But interstellar medium pressure is so tiny that $P_{inf}/P_{surf} \sim 10^{-14}$!! The static solution does not work at all.

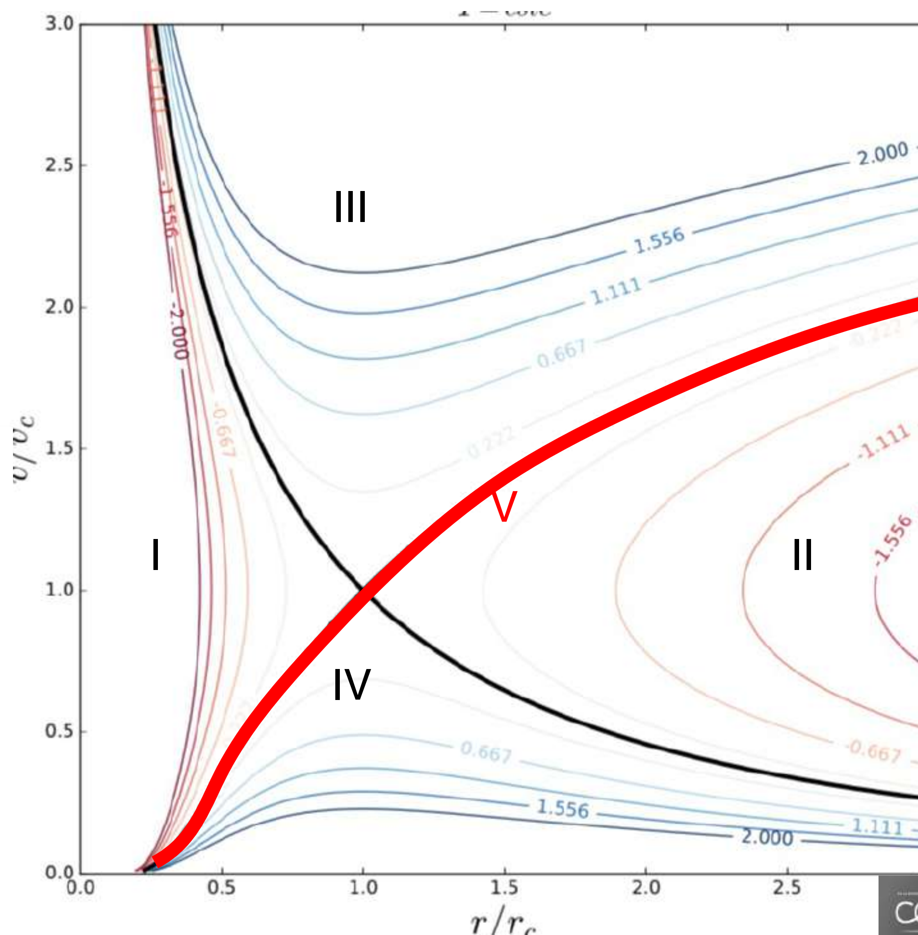
In **1958**, E. Parker proposed that the courona extends as an outflow or stationnary solar wind, making it dynamical and allowing to explain the huge pressure drop vs r (~ $1/r^2$ as density)

$$1/2\,u^2 - c_s^2 \ln u = 2c_s^2 \ln r + GM/r + C$$

I & II: Unphysical 2 velocity for 1 radius
III: No supsersonic wind observed at R_{sun}
IV: unstable solution: accretion (Velli 1994)
V: Parker solution

Mach number $M_s = v/c_s$

Sound speed $c_s = \mathrm{sqrt}(\gamma P/\rho)$



Magnetized Wind: Weber-Davis model

In reality, wind exists in a magnetized environment, so this must be taken into account when calculating our solution as well as the rotation of the star.

The radial component of the momentum conservation equation now becomes

$$\rho v_r \frac{\mathrm{d}v_r}{\mathrm{d}r} = \rho \frac{v_\varphi^2}{r} - \frac{\mathrm{d}P}{\mathrm{d}r} - \rho \frac{GM_\star}{r^2} - \frac{1}{8\pi r^2} \frac{\mathrm{d}(rB_\varphi)^2}{\mathrm{d}r},$$

$$\longrightarrow \left(v_r - \frac{c_s^2}{v_r}\right) \frac{\mathrm{d}v_r}{\mathrm{d}r} = 2\frac{c_s^2}{r} - \frac{GM_\star}{r^2} - \frac{1}{8\pi\rho r^2} \frac{\mathrm{d}(rB_\varphi^2)}{\mathrm{d}r} + \frac{v_\varphi^2}{r}$$

By writing the φ component of the momentum conservation equation, we can further find that

$$L = ru_\varphi - \frac{rB_\varphi B_r}{4\pi\rho u_r} = \text{Constant}$$

which corresponds to the total angular momentum carried by the wind. At the so-called Alfvén surface ($u_r(R_A)=V_{Ar}(R_A)$), uφ diverges, which implies that

$$L = \Omega R_A^2$$

The Alfvén radius R_A acts as a lever arm, slowing down the star through magnetic torque during its lifetime.

Weber & Davis, 1967, Sakurai 1985

Magnetized Wind: Weber-Davis vs Parker model

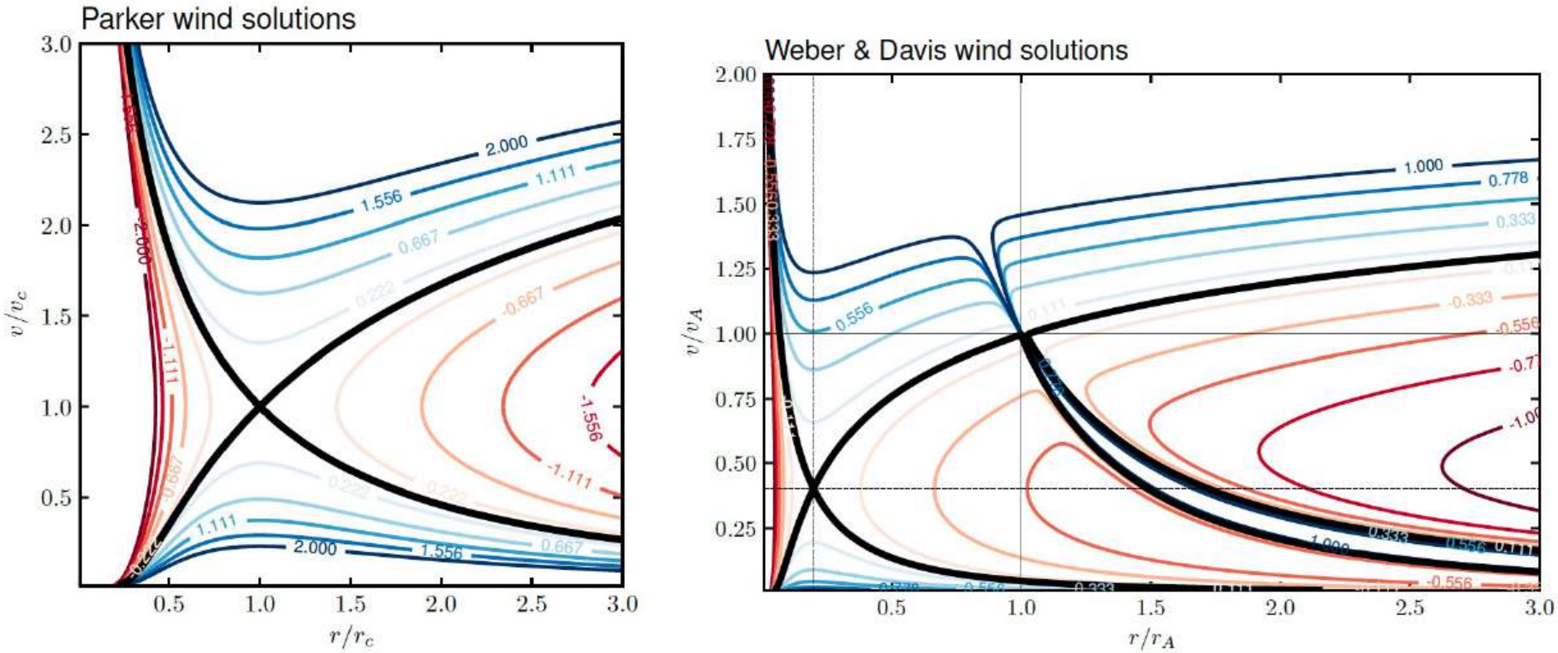
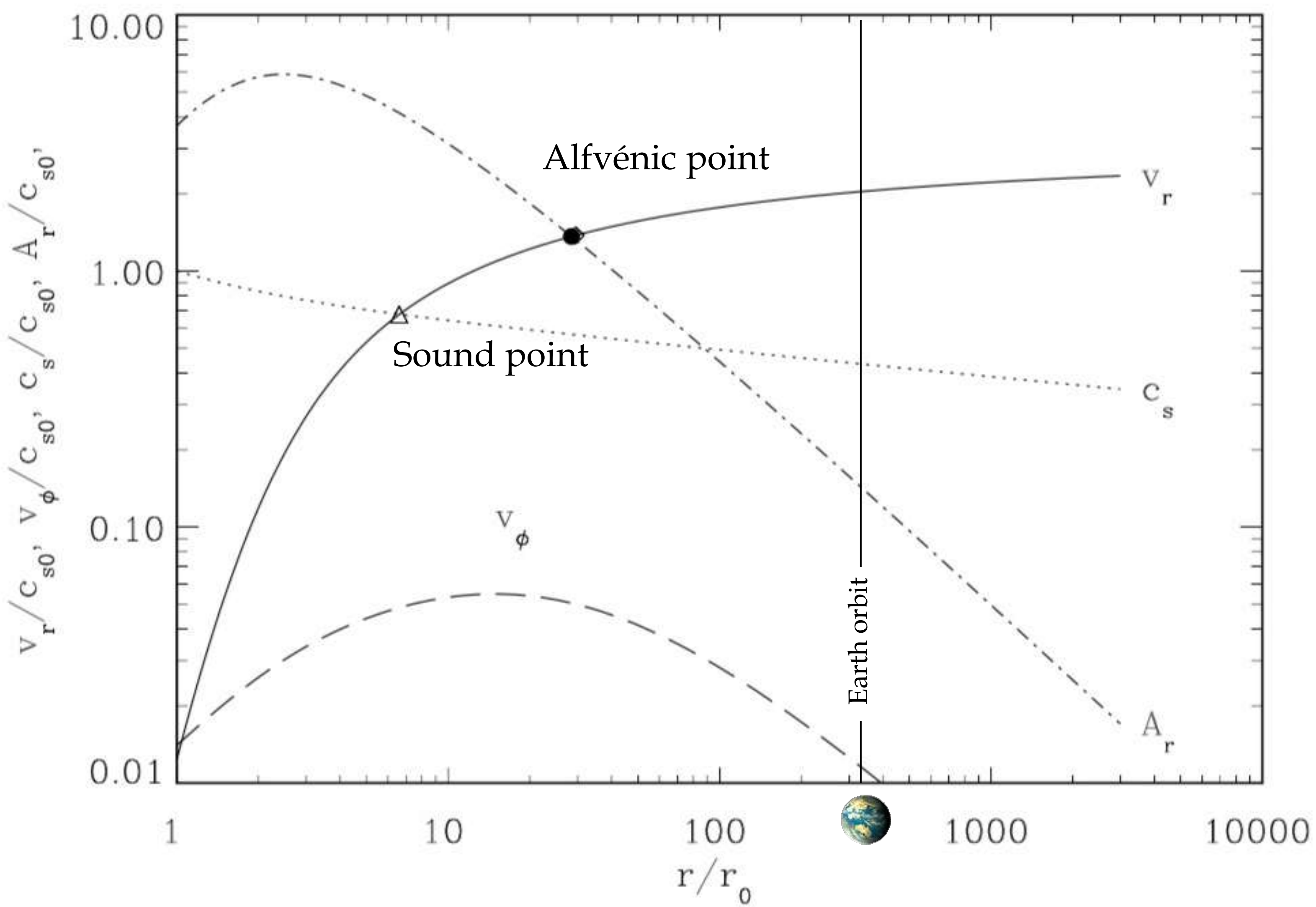


Figure 5. *Left.* Parker wind solution. We show the contours of function $F(M, x)$ (Equation 5). The Mach number is shown as a function of the distance to the star normalized by the critical radius r_c. Each contour is a mathematical solution to the isothermal spherically-symmetric solar wind. *Right.* Weber and Davis wind solution. We show the contours of function $F_A(M_a, x_A)$ (Equation 7), for $r_A = 25\,R_\odot$ and $r_c = r_A/5$, and assuming that $v_c = \sqrt{GM_\odot/r_c}$. The alfvénic Mach number is shown as a function of the distance to the star normalized by the Alfvén radius r_A. Each contour is a mathematical solution to the isothermal spherically-symmetric solar wind under the influence of rotation and magnetism. Note that on the bottom left, we recover a Parker-like wind solution (left panel).

Magnetized Wind: Weber-Davis model



MHD Wind Simulations

Why are they necessary ?

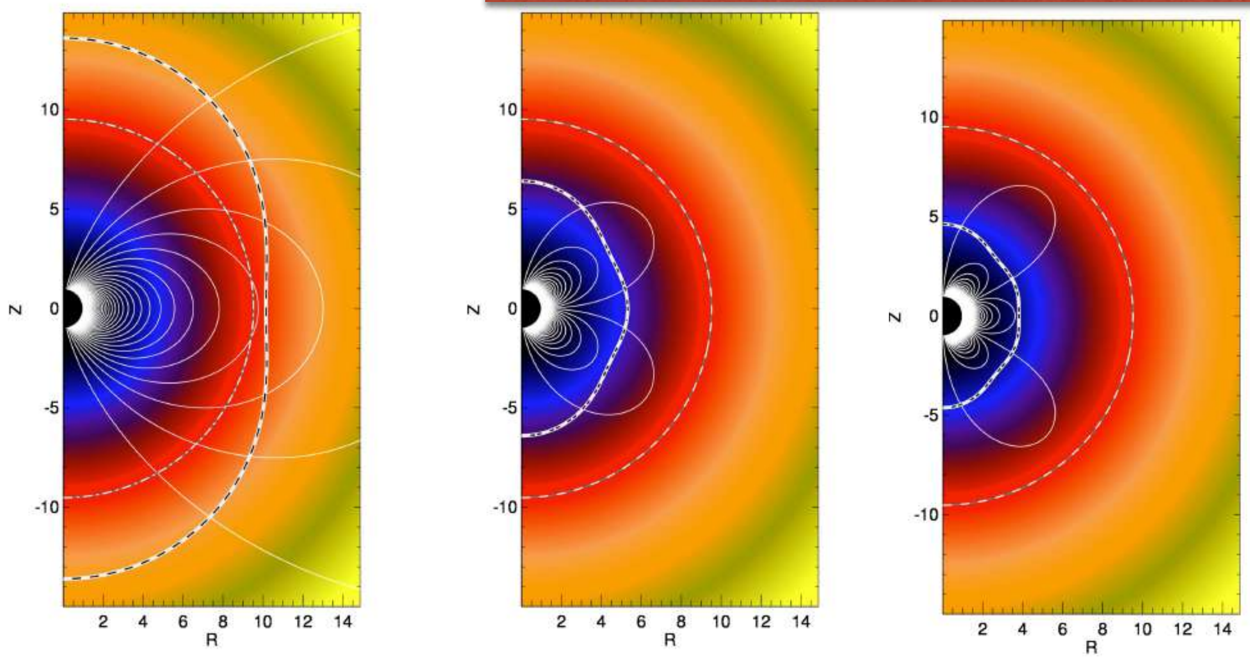
- Magnetic fields > split monopole
- Rotation
- 3D, non-axisymmetry

Parametric study of the torque as a function of:

Rotation
Magnetic field strength
Magnetic field topology

Coronal temperature and gamma held fixed.

Decreasing Alfvén surface !



Dipole *Quadrupole* *Octupole*

60 cases with compressible MHD code PLUTO

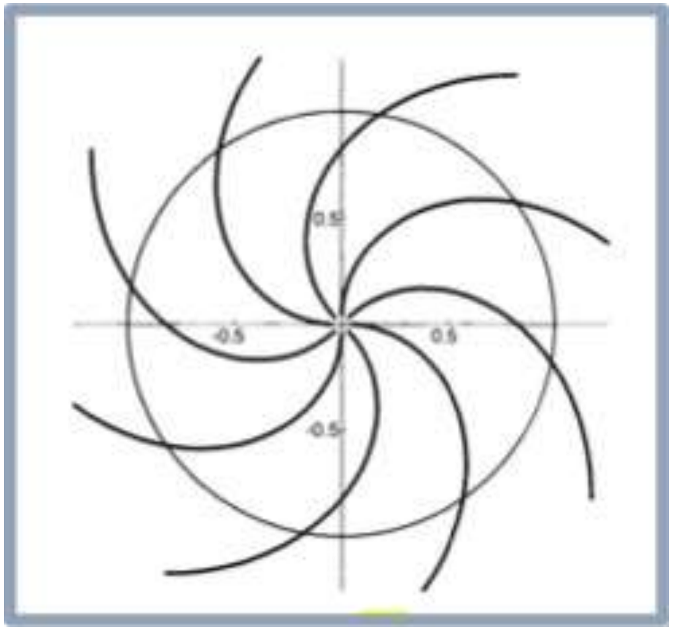
(Réville et al. 2015, ApJ)

Mass and Angular Momentum Loss by Solar Wind

Spin down through magnetic braking (Schatzmann 1962)

Weber & Davis (1967)

Lever arm



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

Angular momentum loss

The azimuthal magnetic field does not suddenly change from straight to spiralled. But quantitatively, it all works out *as if* there was a sharp transition. Following this picture, one can define an average Alfvén radius $\langle r_A \rangle$ — an "effective lever arm length". The specific angular momentum flux rate is then

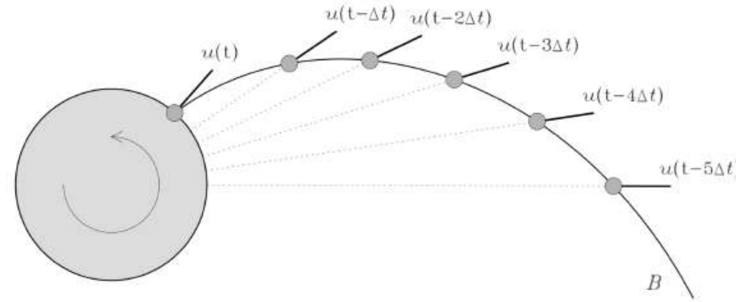
$$l = \Omega_0 \langle r_A \rangle^2 \ . \tag{7}$$

The resulting torque applied on the sun is (Matt & Pudritz 2008)

$$\tau = -\dot{M} \Omega_0 \langle r_A \rangle^2 \ . \tag{8}$$

Parker Spiral (Parker 1958)

$$\phi(\varpi) = -\Omega_\odot \frac{\varpi - R_\odot}{u_{sw}} + \phi_0$$



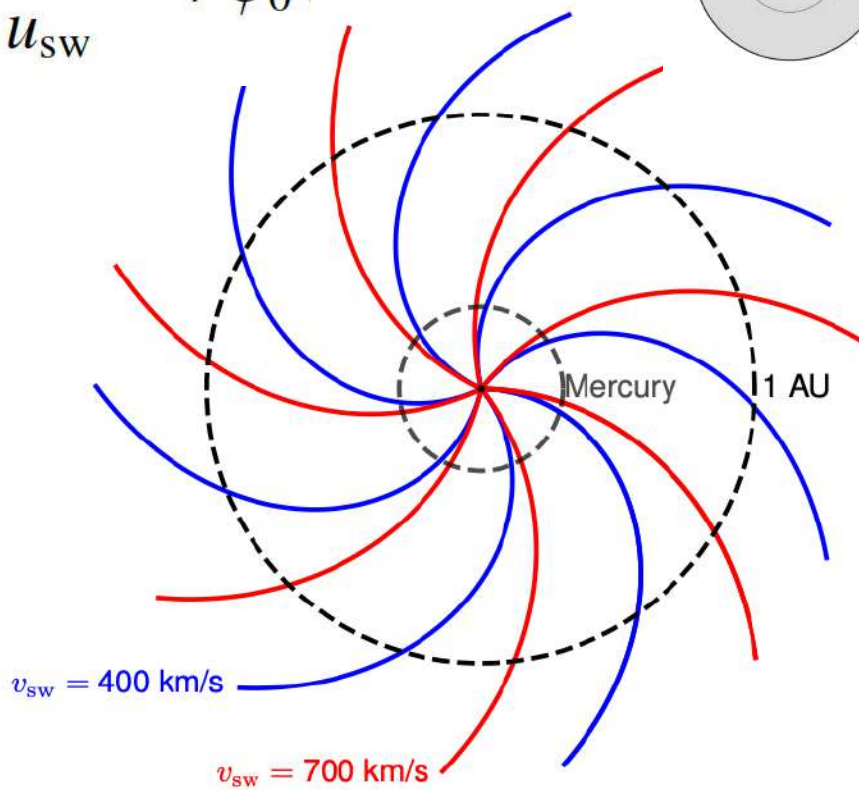


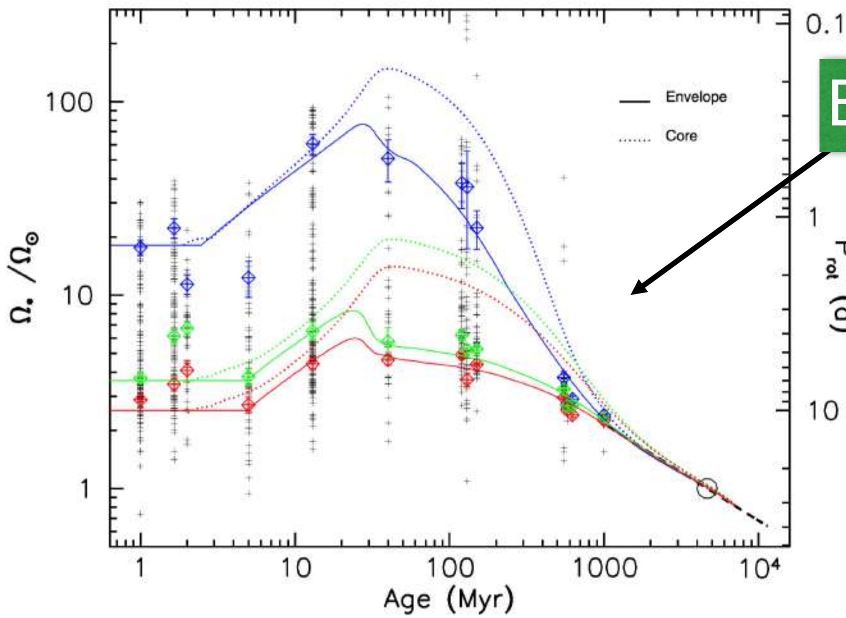
Figure 5.12 – Parker interplanetary magnetic spiral for $v_{sw} = 400$ km/s (blue) and $v_{sw} = 700$ km/s (red). The Earth orbit is labeled by the black dashed circle, and the orbit of Mercury by the gray dashed circle.

Brun & Strugarek 2018

Wind, Stellar evolution and gyrochronology

Stellar Spin down Models

(Gallet & Bouvier 2013)



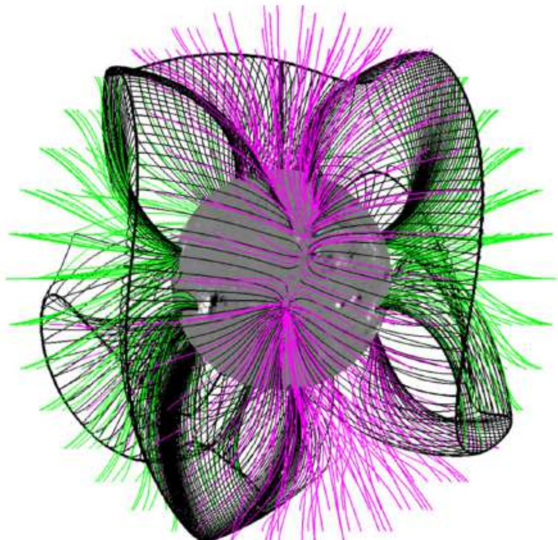
Braking models

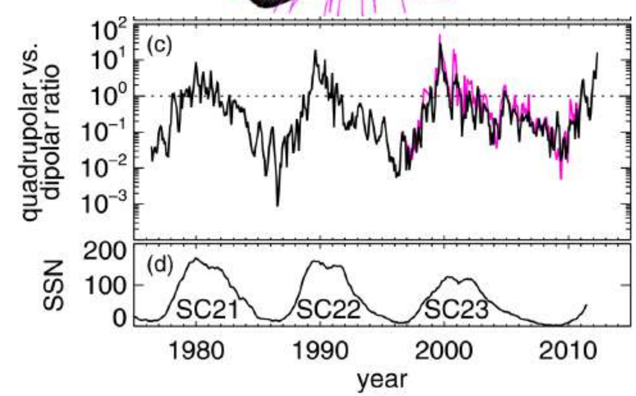
dynamo

wind

Magnetic Activity

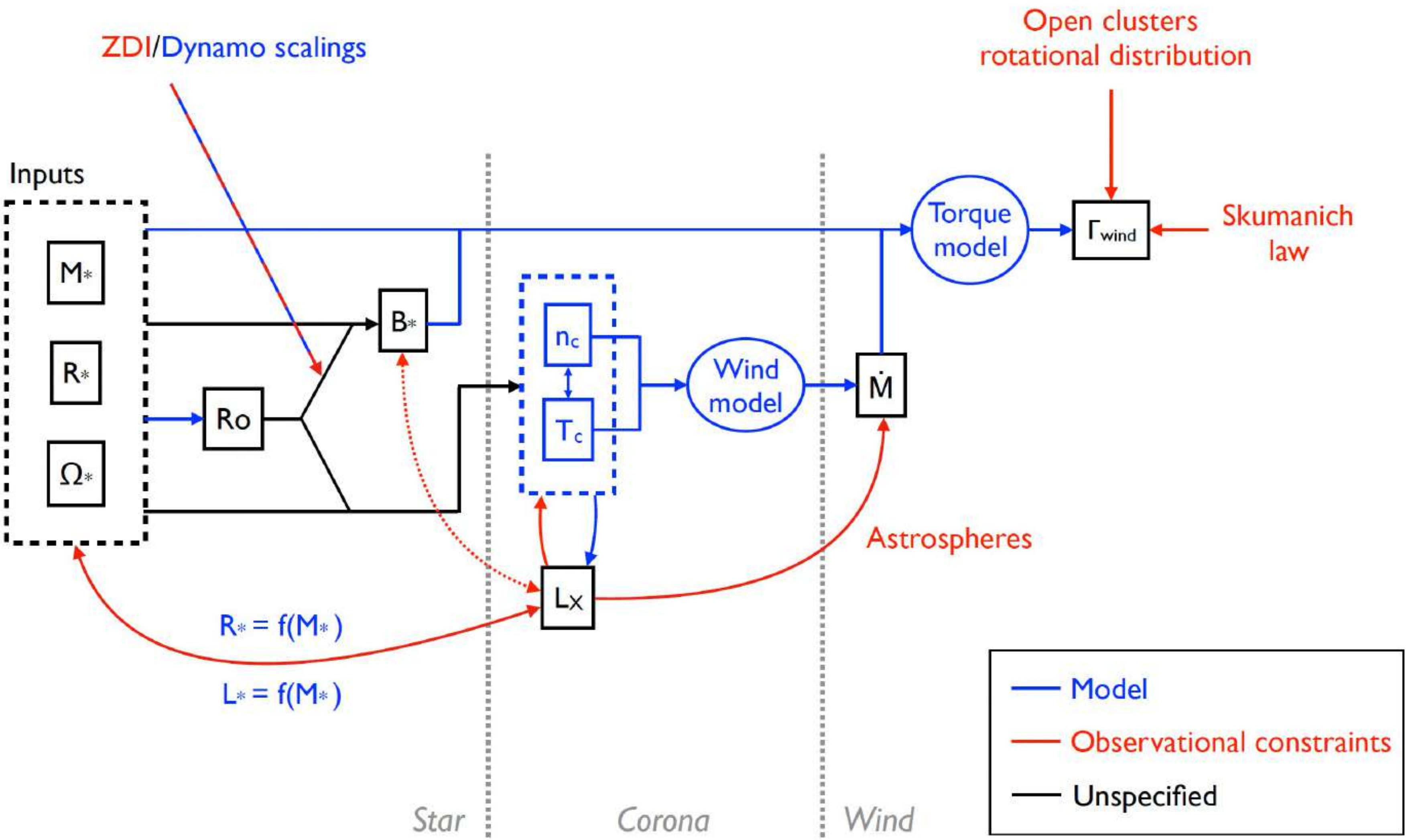
(De Rosa et al. 2012)





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

A coupled dynamo-wind-rotation system



Ahuir, Brun, Strugarek 2020

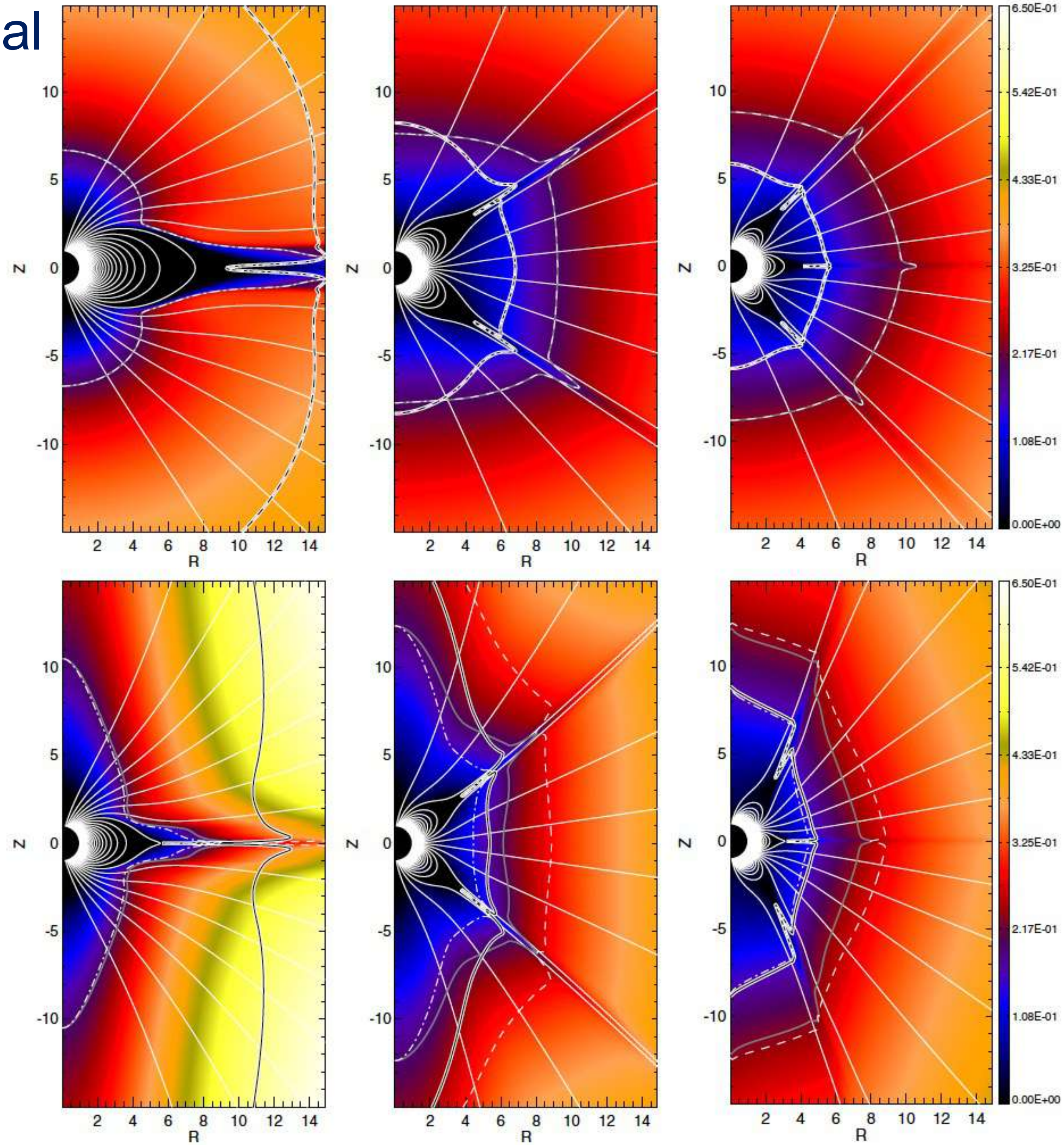
Magneto-Centrifugal Effect

Sakurai 1985

Slow rotation

Fast rotation

Reville et al. 2015a



Angular Momentum Loss from Wind Simulations

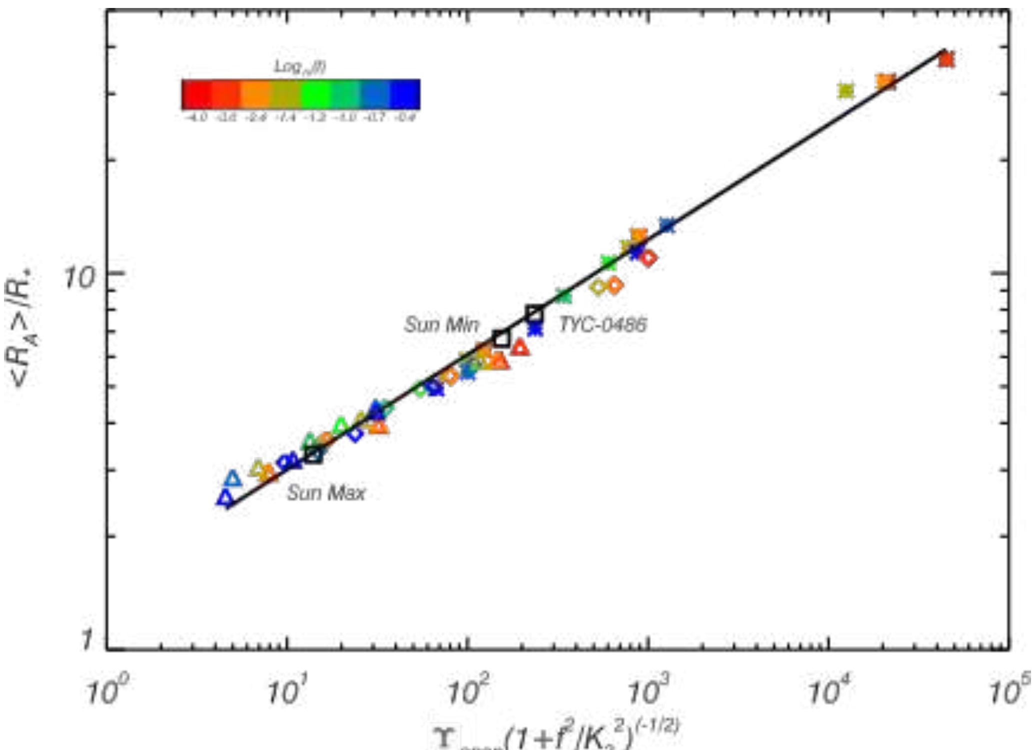
The most general law as of today:

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

open flux

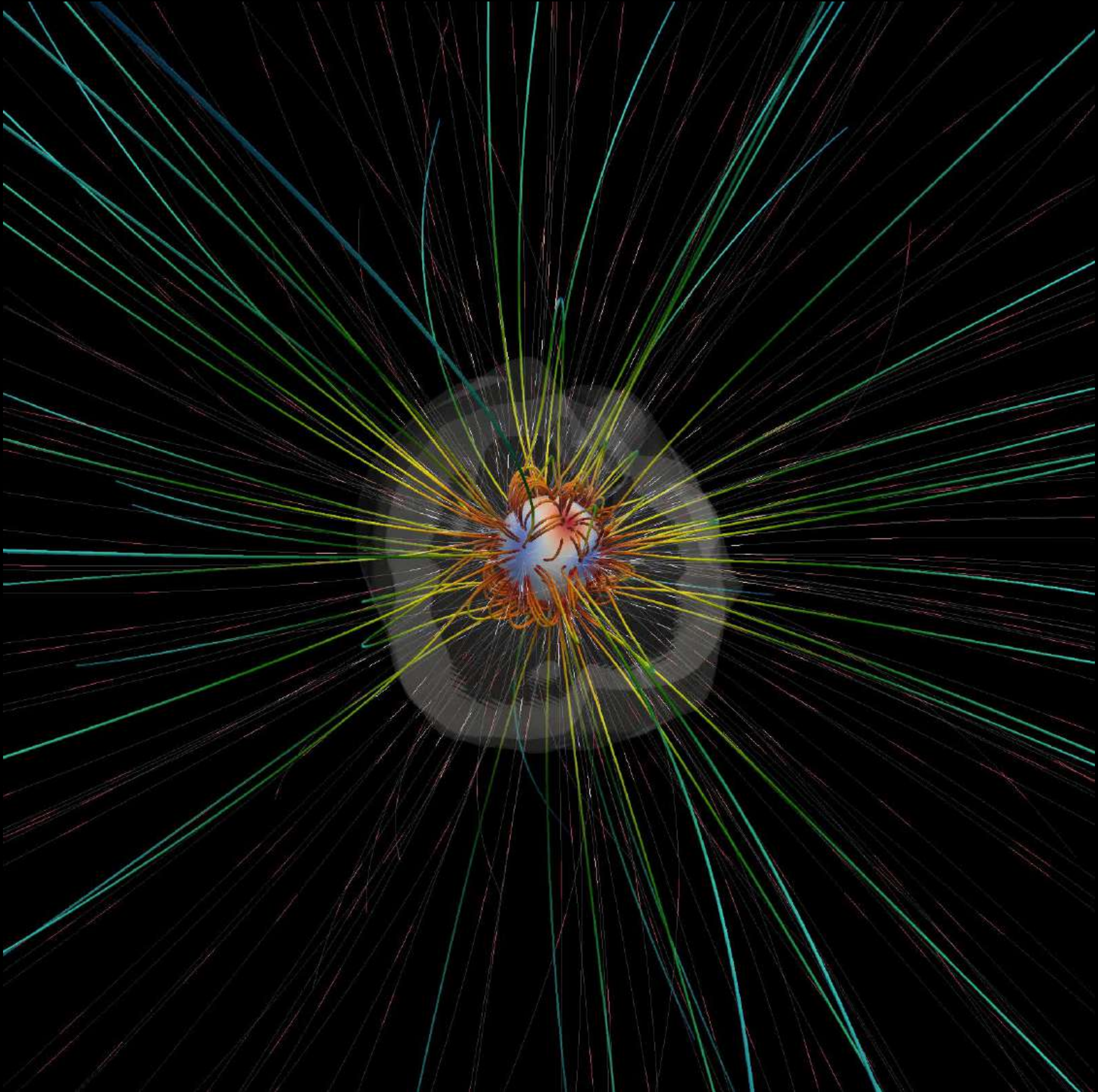
$$\Phi_{open} = \int_S |\vec{B} \cdot d\vec{S}|$$

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

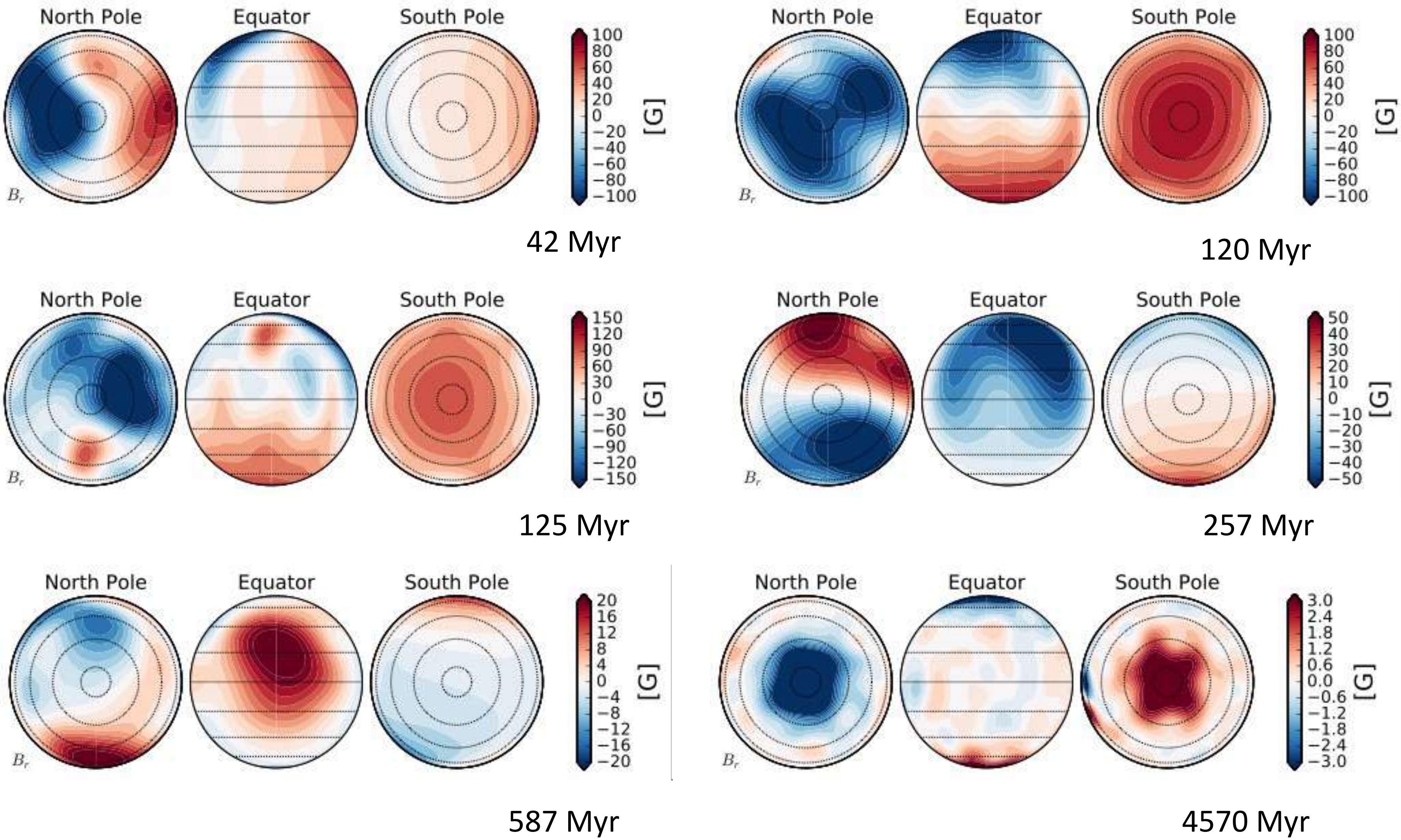


m=0.31
K1=0.64
K3=0.06

Réville et al. 2015a, ApJ 798:116

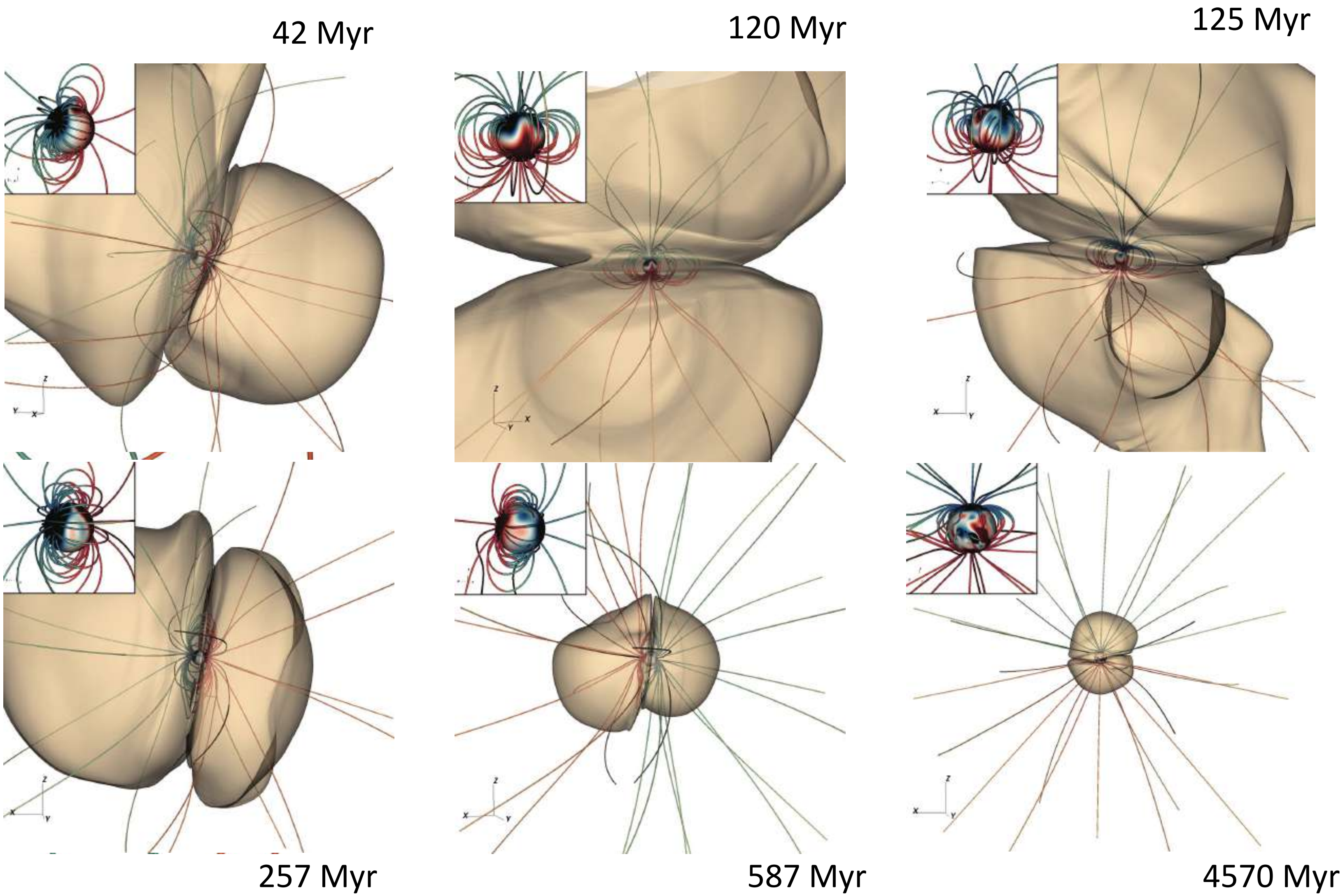


Complex magnetic topologies



[Réville+ 2016]

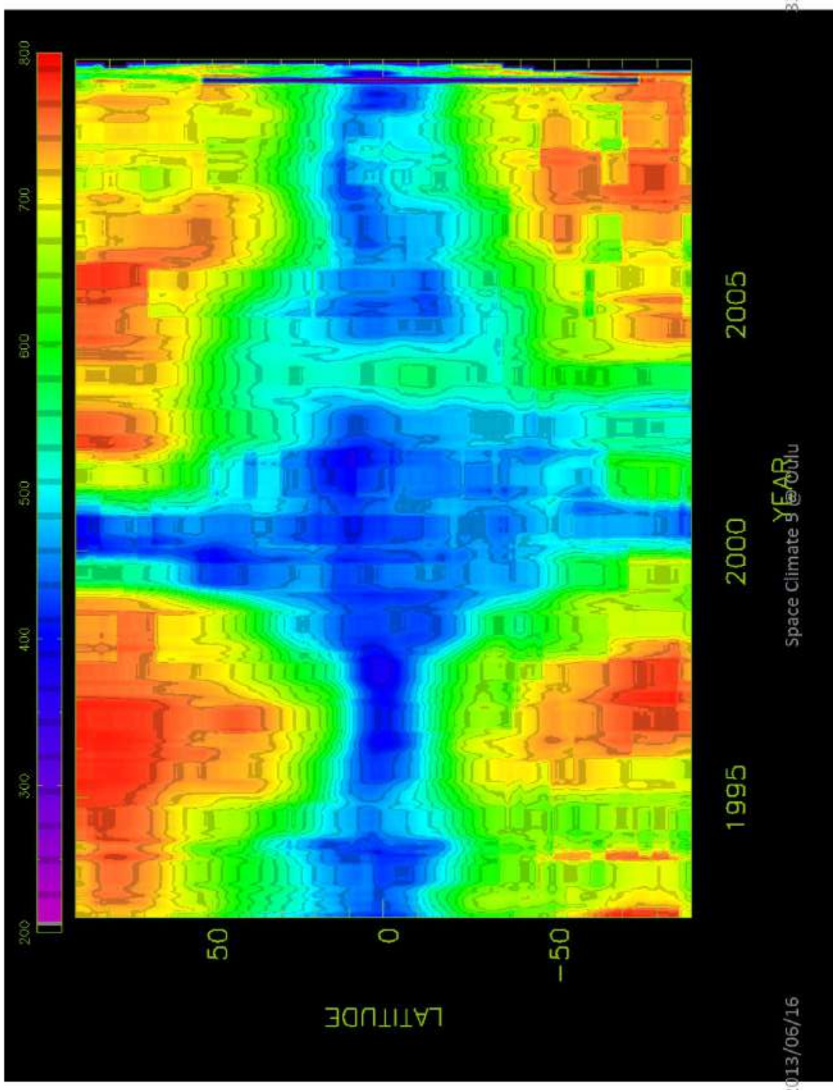
Complex magnetic topologies



[Réville+ 2016]

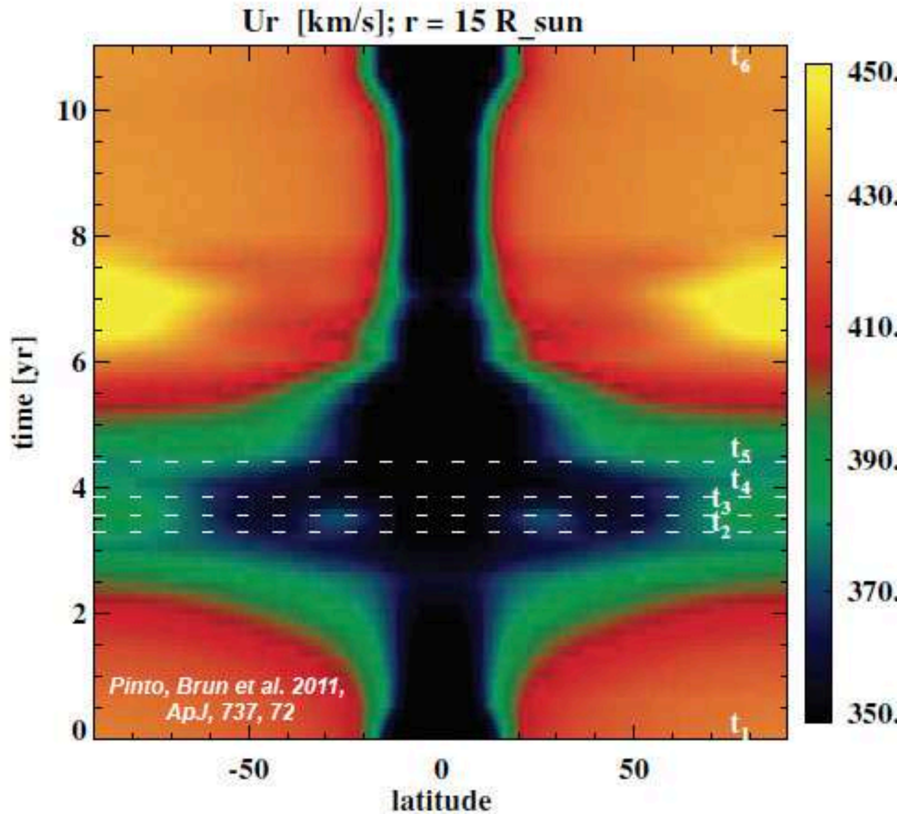
11-yr Cycle Variations of Solar Wind

Solar Wind Speed



Observations (IPS@ 327 MHz)

Tokumaru et al. 2010, Sokol et al. 2015



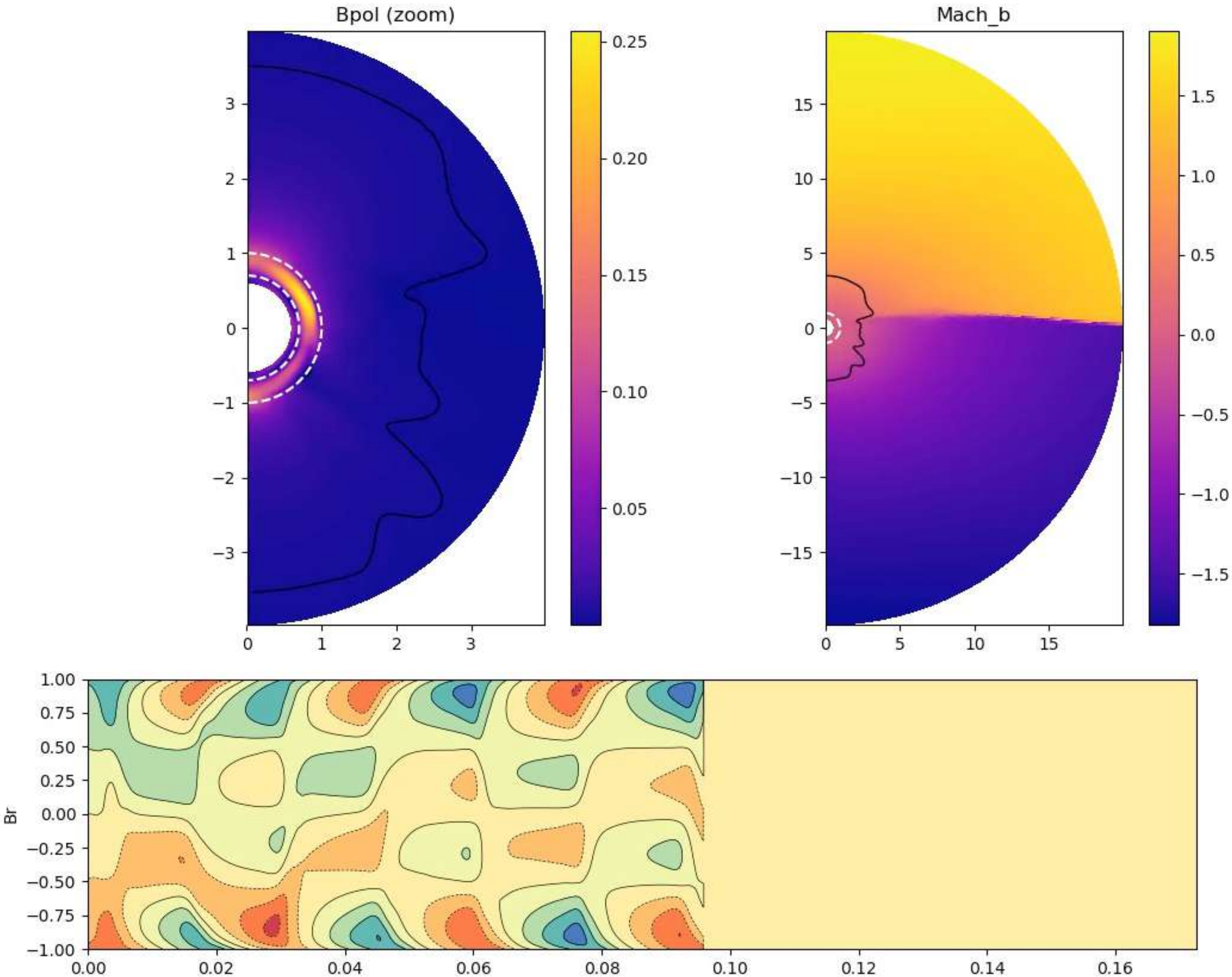
Dynamo-wind model

Pinto, Brun et al. 2011

DYNAMICAL COUPLING DYNAMO & WIND

ANSWERING SOLAR ORBITER MAIN QUESTION

Perri, et al. 2021
Perri et al. 2022



Two layers stellar rotation model

Angular momentum J

$J_{core}=I_{core}\Omega_{core}$
$J_{env}=I_{env}\Omega_{env}$

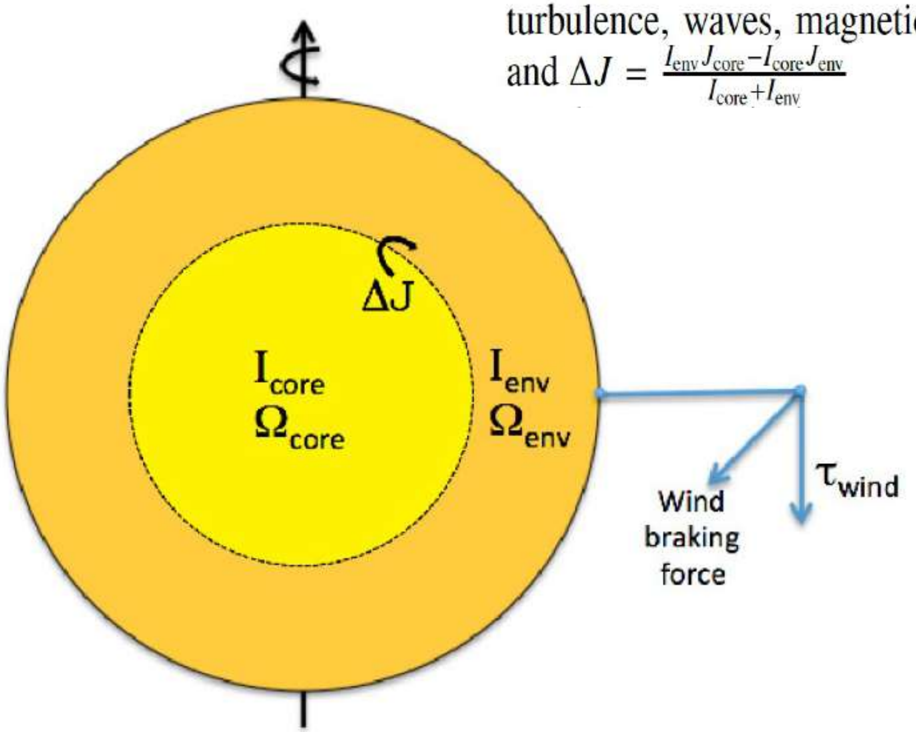
Inertia: $I_* = k^2 M_* R_*^2$

If an external torque, such as the one coming from a stellar wind is applied to the star, the angular momentum evolution of the convective envelope and radiative interior can be expressed as [28]:

$$\frac{dJ_{core}}{dt} = -\frac{\Delta J}{t_c}$$
$$\frac{dJ_{env}}{dt} = \frac{\Delta J}{t_c} - \frac{J_{env}}{t_w},$$

with t_c the coupling time scale between the two zones due to the combined action of turbulence, waves, magnetic fields and viscous stresses and t_w the wind braking timescale and $\Delta J = \frac{I_{env}J_{core}-I_{core}J_{env}}{I_{core}+I_{env}}$

With such stellar simple rotation model we can easily make secular evolution Computation of solar type stars.



Brenner & McGregor 1991

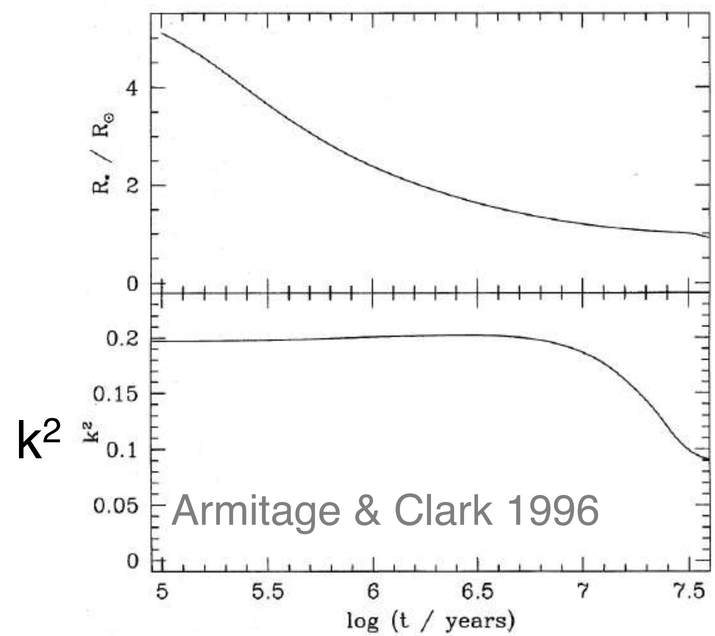
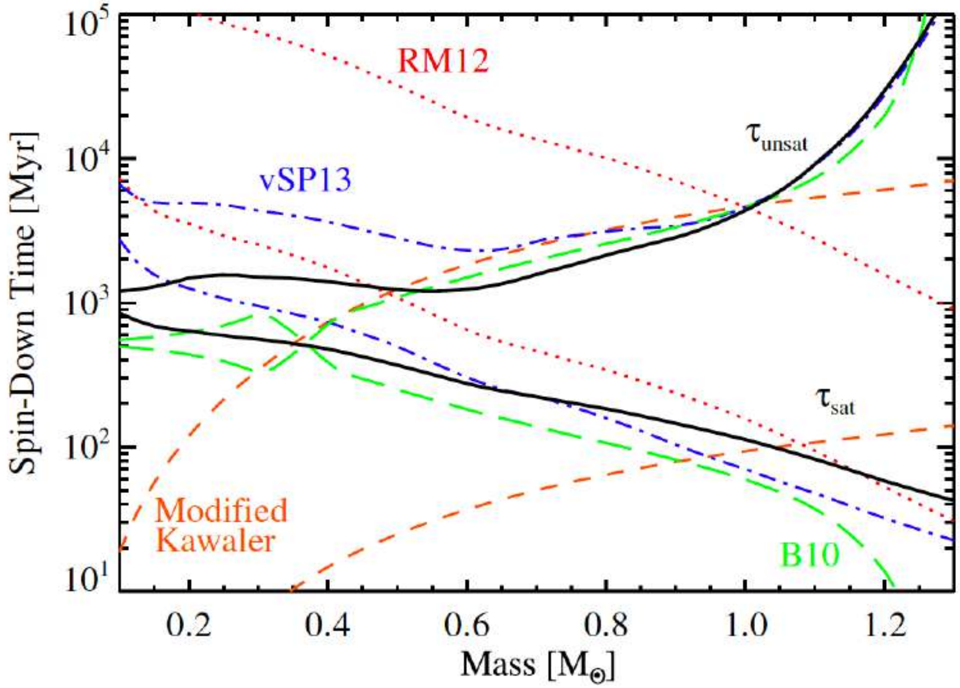
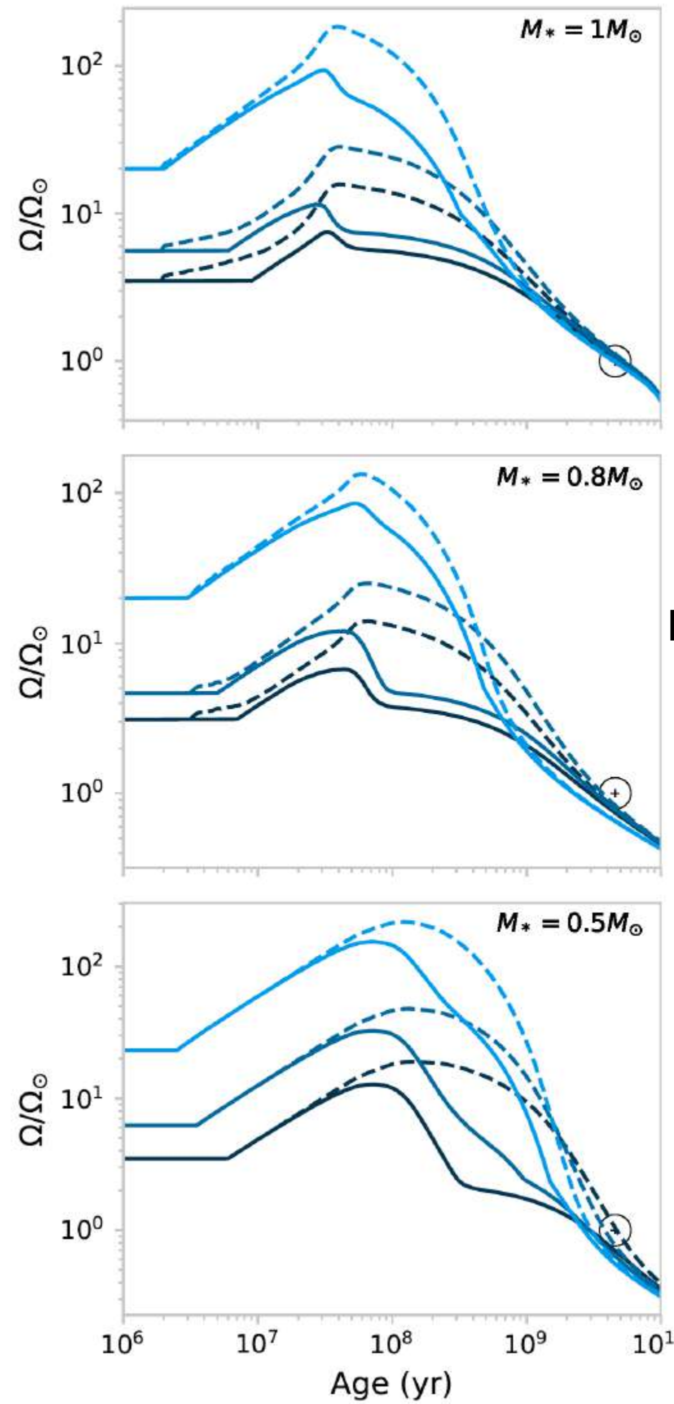


Figure 1. Evolution of the stellar radius R_* and squared radius of gyration k^2 for the 0.9985 $M_\odot$ stellar model.

Stellar wind brake down vs Mass

When the star leaves the rotation saturated state, the torque changes its dependence with mass. F stars spin down faster than M stars And then this trend reverses.





Rotation history vs M*

Matt, Brun et al. 2015, ApJ
Benbakoura, Brun et al. 2019
Ahuir et al. 2021

Stellar rotation in clusters vs time

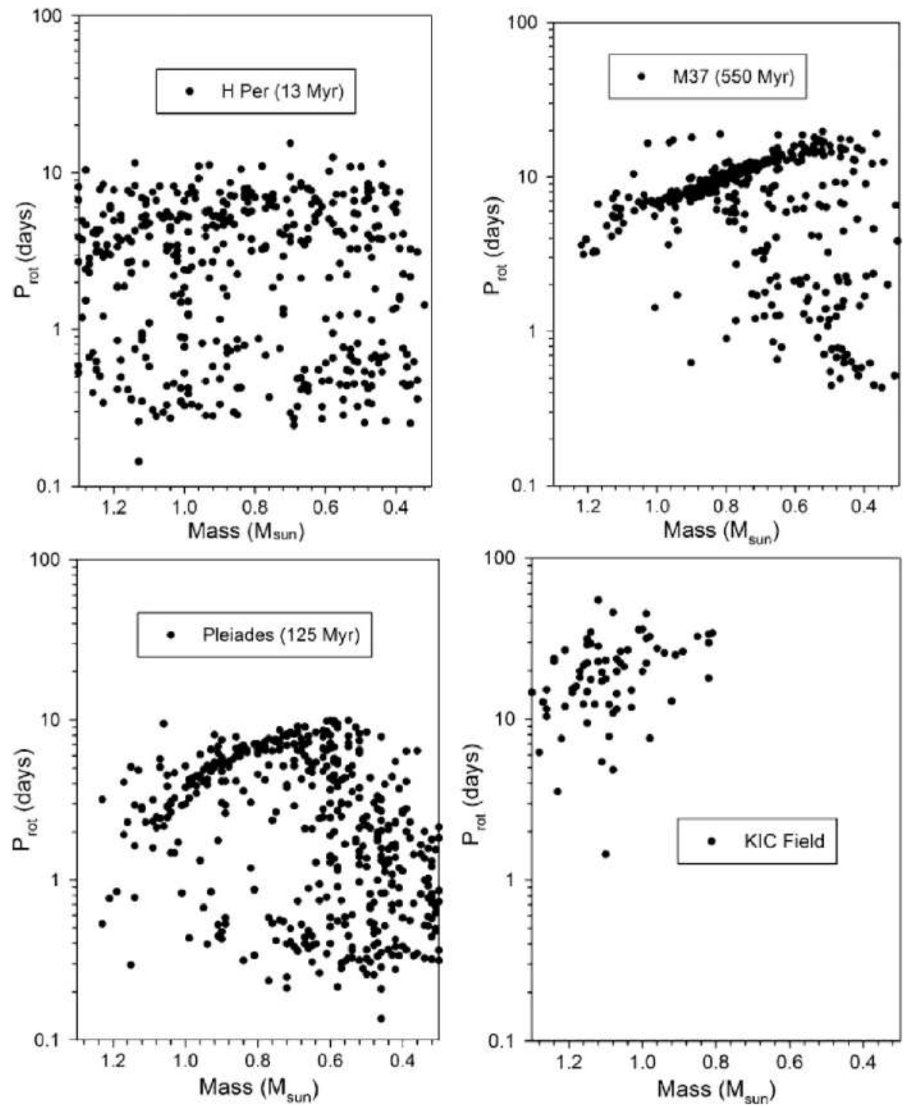
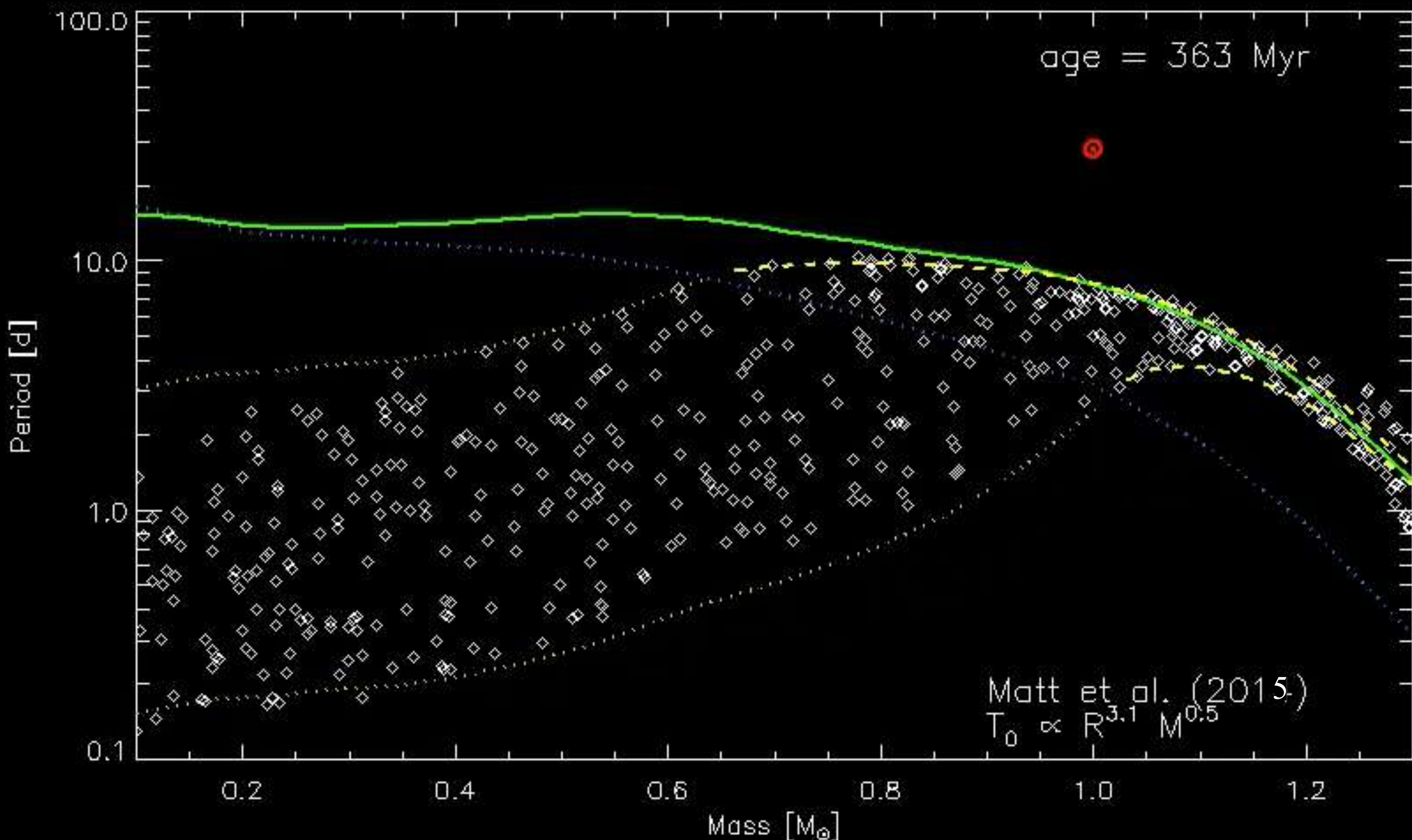


Figure 7.1 – Stellar cluster rotation period distribution vs stellar mass and age, showing the convergence of solar-type stars rotation rate toward a clear sequence with little spread. (adapted from Brun et al. 2015).

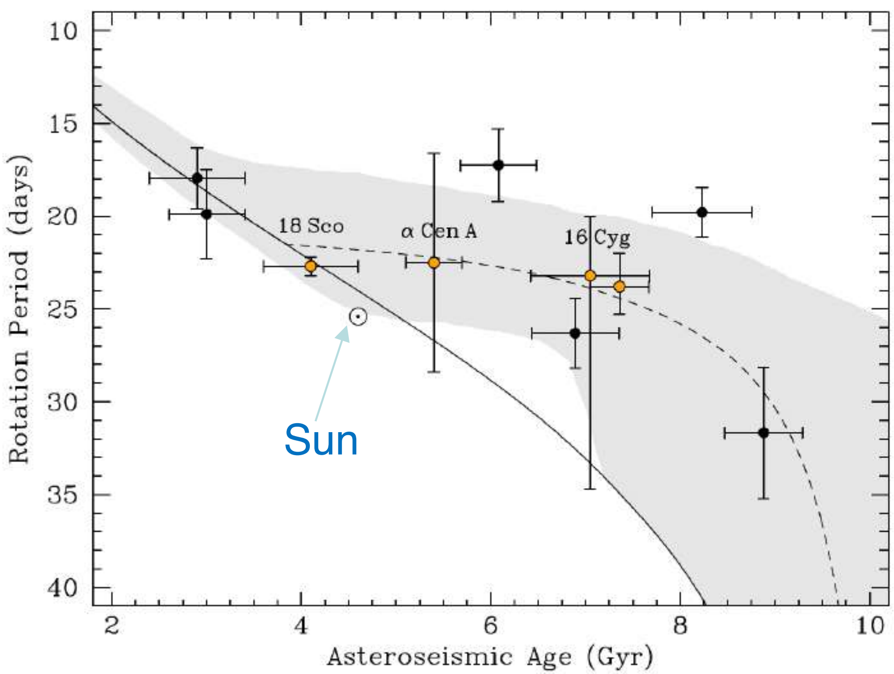
Stellar Cluster Rotation Evolution vs M*



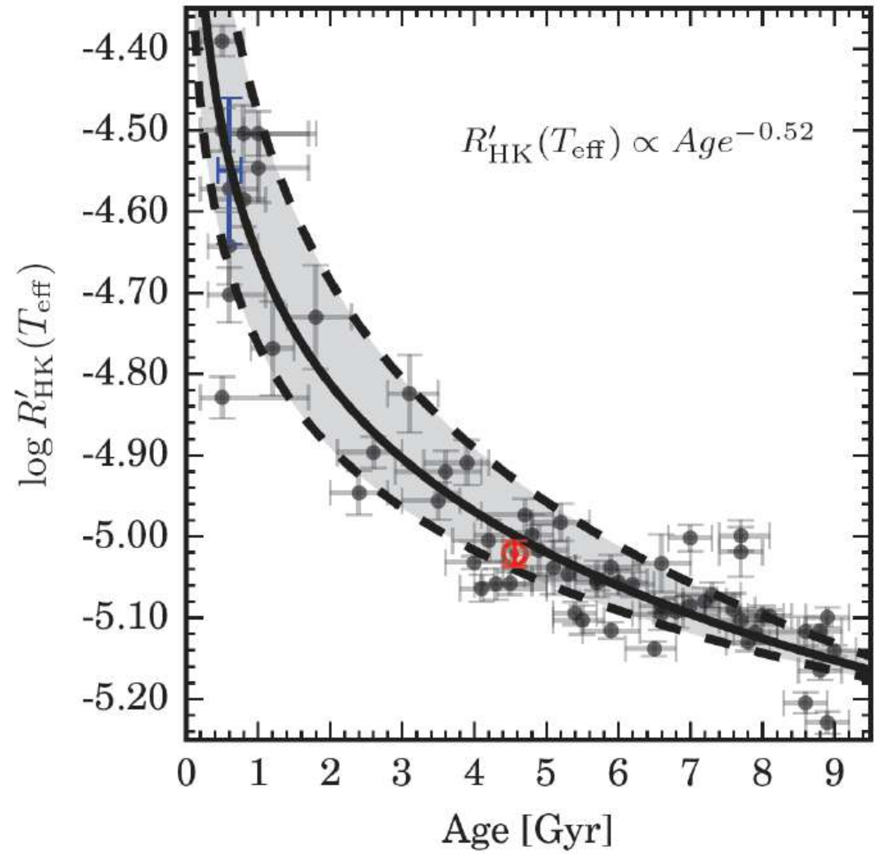
Matt, Brun et al. 2015, ApJ

Break of Gyrochronology or not?

(e.g. Age-rotation Skumanich's law)



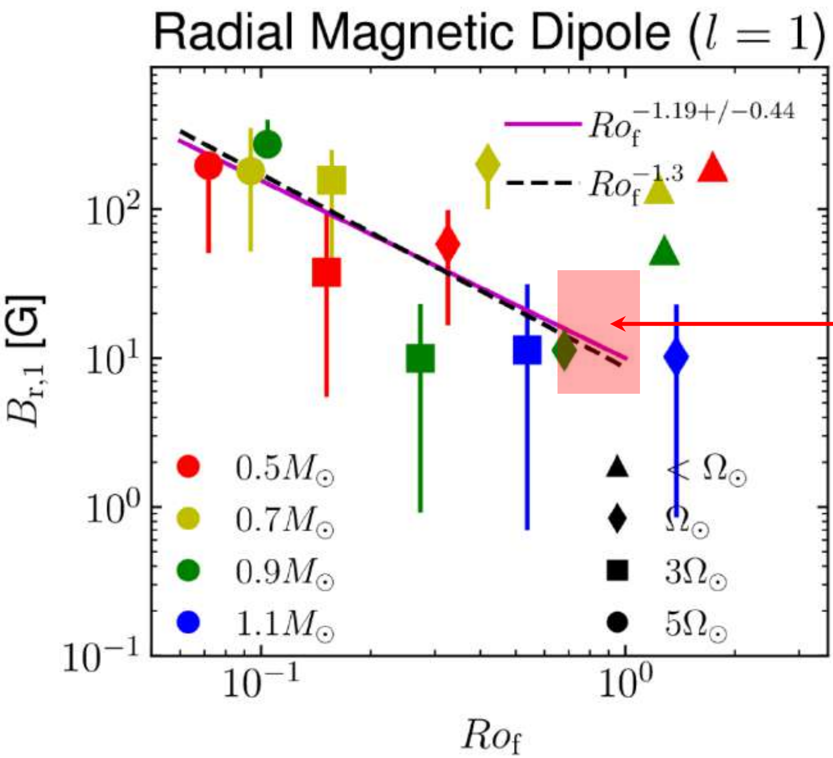
Metcalfe & Van Sader 2017
Hall et al. 2021



Lorenzo-Oliviera et al. 2018

Recovering Observational Trends

Brun, Strugarek, Noraz+ 22



- The dipole decreases but does not disappear

However, there may be a minimum around the solar Rossby value

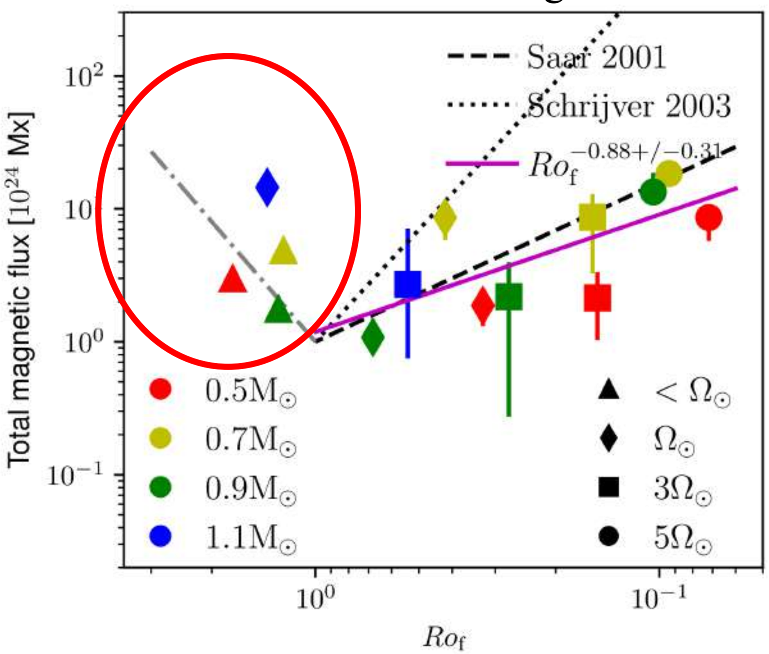
- Can a star be trapped in this regime by a **combination of magnetism and mass loss rate?**

$$\dot{J} \propto \dot{M}\Omega_* \langle r_A \rangle^2$$

Larger global field in slowly rotating stars?

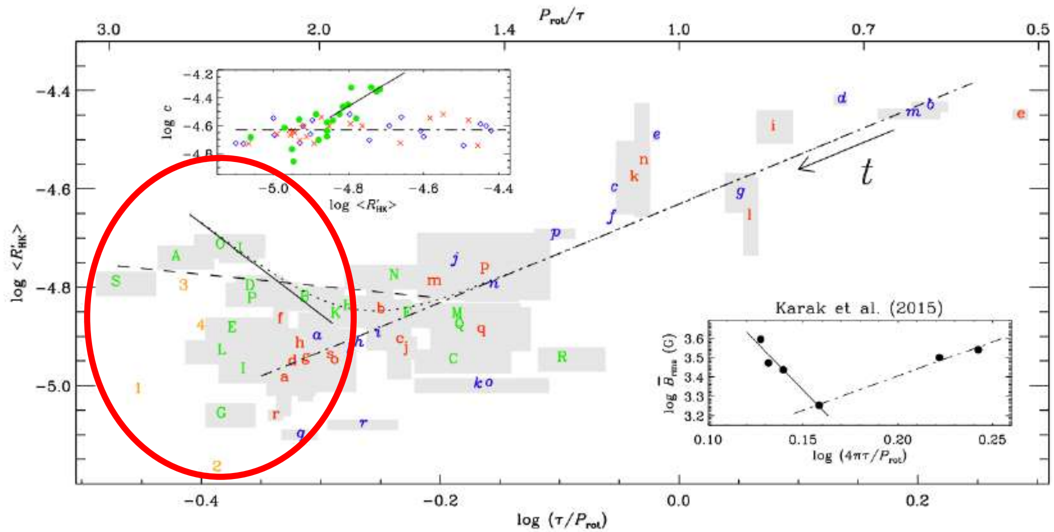
Brun, Strugarek, Noraz+ 22

Possible increase of the magnetic flux

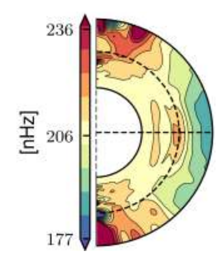


Brandenburg & Giampapa 18

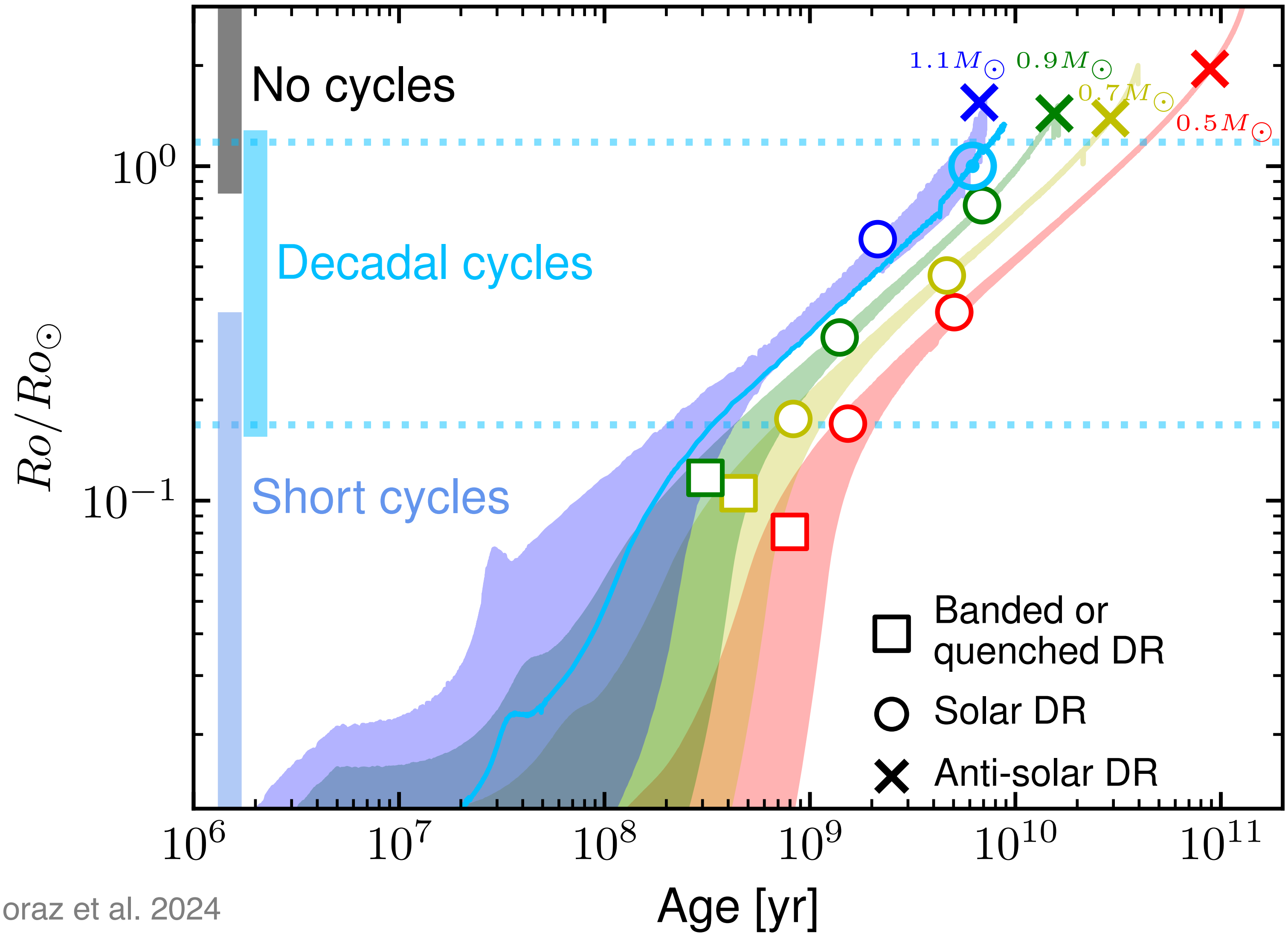
Possible enhancement of the activity



- Need **theoretical** and **observational constraints** to enlighten what occurs in the anti-solar regime



A plausible « Sun in time » story



Noraz et al. 2024

Next Lecture:

Space Weather