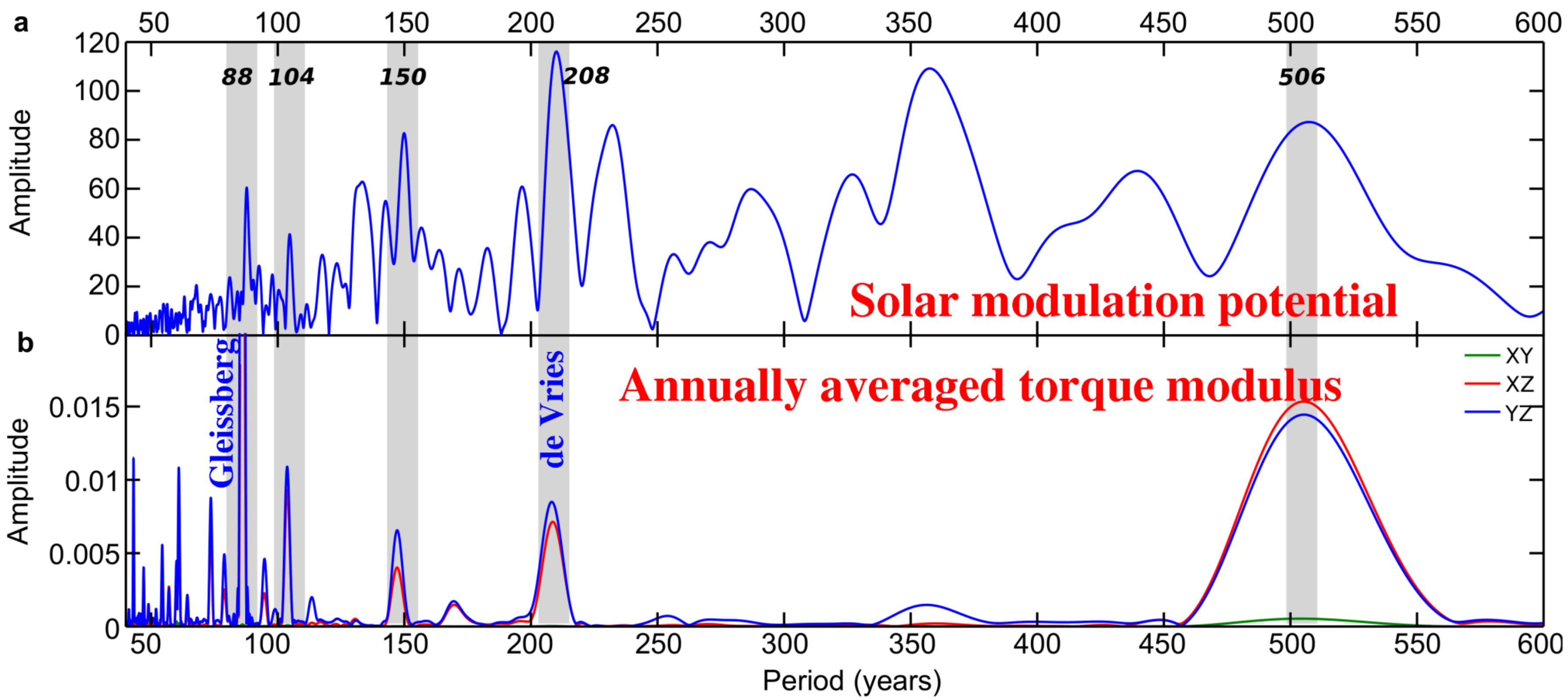
KIS Thinkshop 2018
Planetary-Stellar Connection: The Sun's Lesson
Freiburg, May 7-9 2018

Tidally synchronized Babcock-Leighton and Tayler-Spruit type dynamos

Frank Stefani, André Giesecke, Norbert Weber, Tom Weier

HZDR
HELMHOLTZ ZENTRUM DRESDEN ROSSENDORF

Planetary motion and long periods



Abreu et al., Astron. & Astrophys. 548 (2012), A88

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Outline

1. Planetary tides and the solar cycle
2. Solar dynamo models
3. Synchronized Babcock-Leighton type dynamos
4. Tayler-Spruit dynamo and the helicity question
5. Resonant excitation of helicity oscillations
6. A simple, and a slightly more complicated model of a synchronized dynamo
7. Summary and prospects (Lithium depletion)

Planetary tides and the solar cycle

Planetary tides and the solar cycle: an old idea of R. Wolf

the researches commenced in the seventh number. I shall accordingly show, by employing, on the one hand, my own observations in the year 1849 to 1858; and on the other, extracts from the observations of Schwabe in the years 1826 to 1848, that the formula

$$M = 50{\cdot}31 + 3{\cdot}73 \left\{ \begin{array}{l} 1{\cdot}68 \sin 585^{\circ}{\cdot}26\, t + 1{\cdot}00 \sin 360^{\circ}\, t + \\ 12{\cdot}53 \sin 30^{\circ}{\cdot}35\, t + 1{\cdot}12 \sin 12^{\circ}{\cdot}22\, t \end{array} \right\}$$

in which t denotes the number of years elapsed since a period of mean spot-frequency, gives a curve very similar to the sun-spot-curve; and therefore is very fit to be taken as the foundation of the more detailed research which I have now in hand. Now, as the coefficients of the four sines are the values which the fraction $\frac{m}{r^2}$ assumes, when for m and r are successively substituted the masses and mean distances of *Venus, Earth, Jupiter, and Saturn*; and the angles of the four sines are the values of $\frac{360^{\circ}}{t}$, when for t are substituted the periodic times of

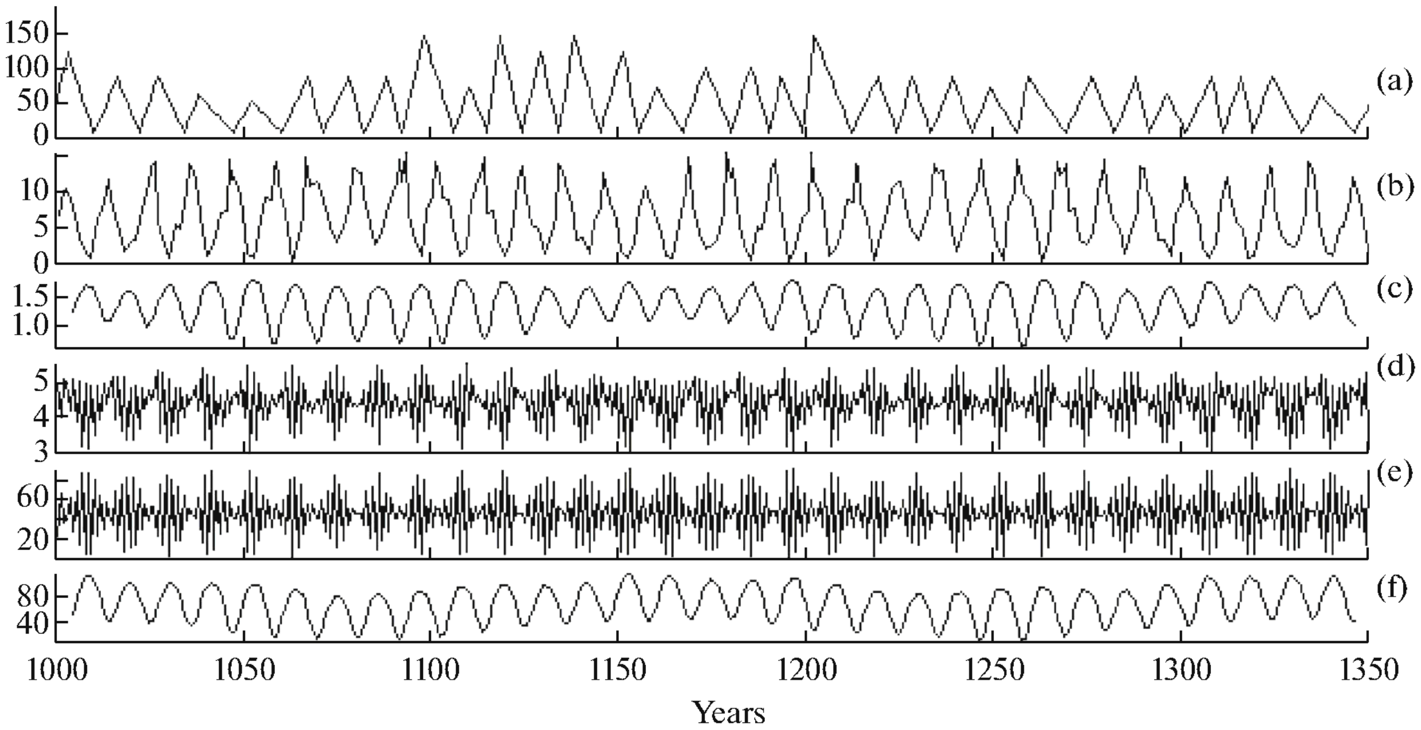
Wolf, R., Mon. Not. R. Astron. Soc. 19 (1859), 85

Planetary tides and the solar cycle: Venus-Earth-Jupiter alignments

Amazing synchronization of solar cycle with the 11.07 years alignment cycle of the Venus-Earth-Jupiter system (despite tiny tidal forces!)

Sunspots

VEJ index



Bollinger, Proc. Okla. Acad. Sci. 33 (1952), 307; Takahashi, Solar. Phys. 3 (1968), 598; Wood, Nature 240 (1972), 91; Wilson, Pattern Recogn. Phys. 1 (2013), 147; Okhlopkov, Mosc. U. Bull. Phys. B. 69 (2014), 257; **Okhlopkov, Mosc. U. Bull. Phys. B. 71 (2016), 444**; Scafetta, Pattern Recogn. Phys. 2 (2014), 1

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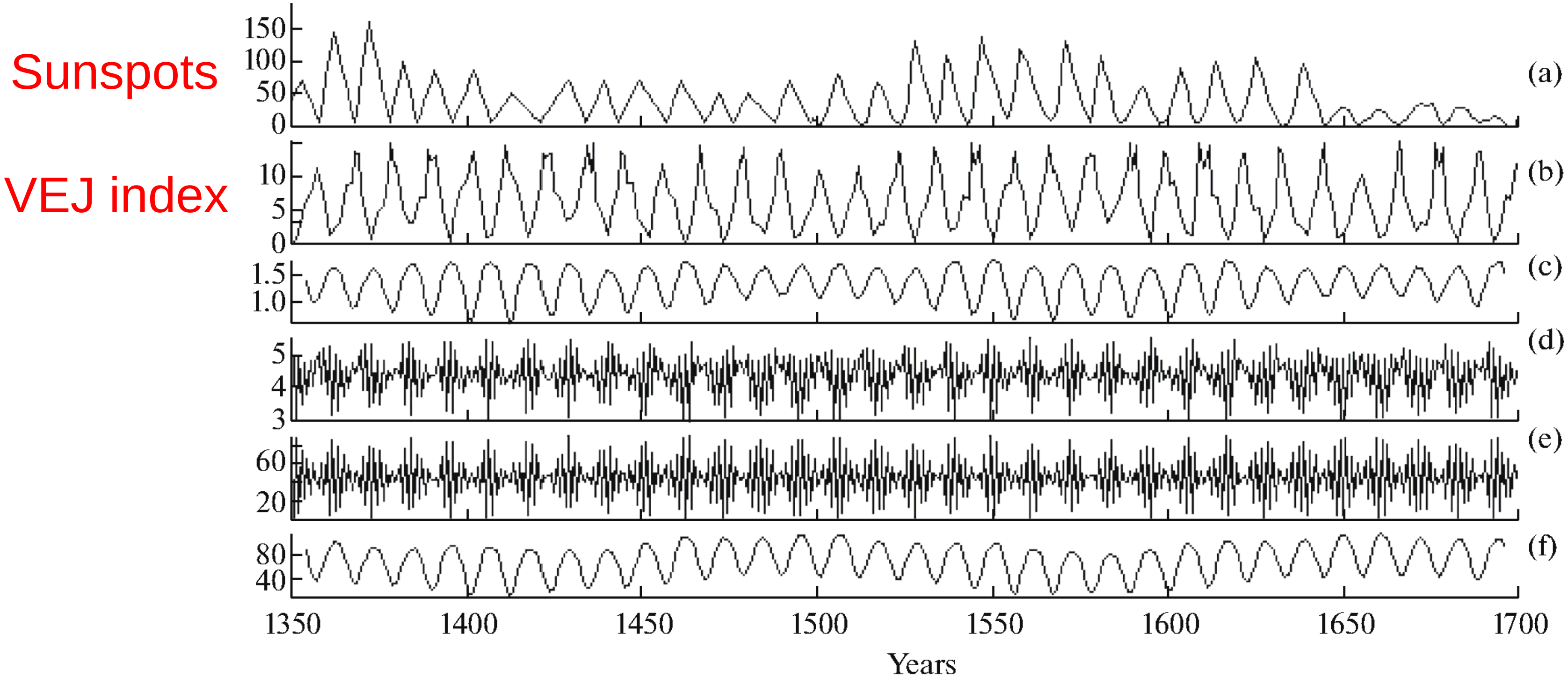

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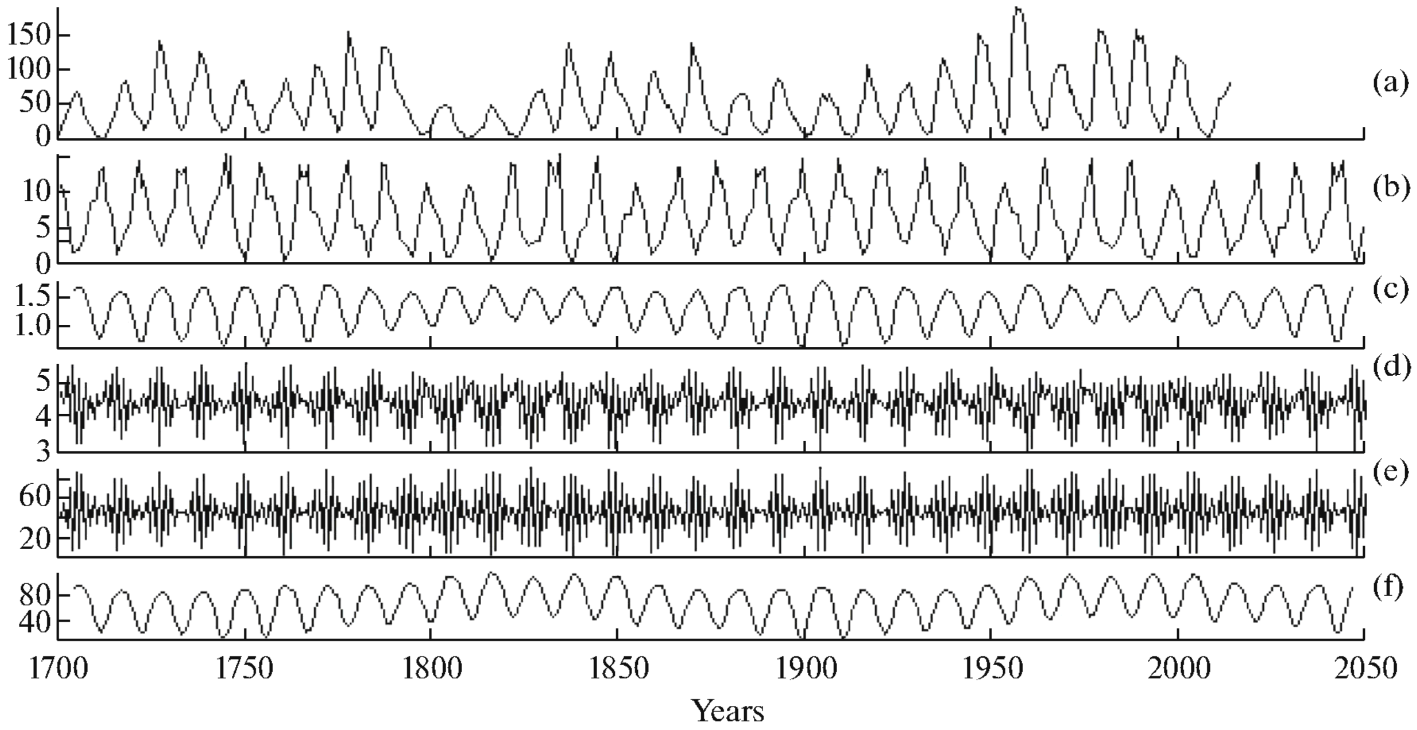

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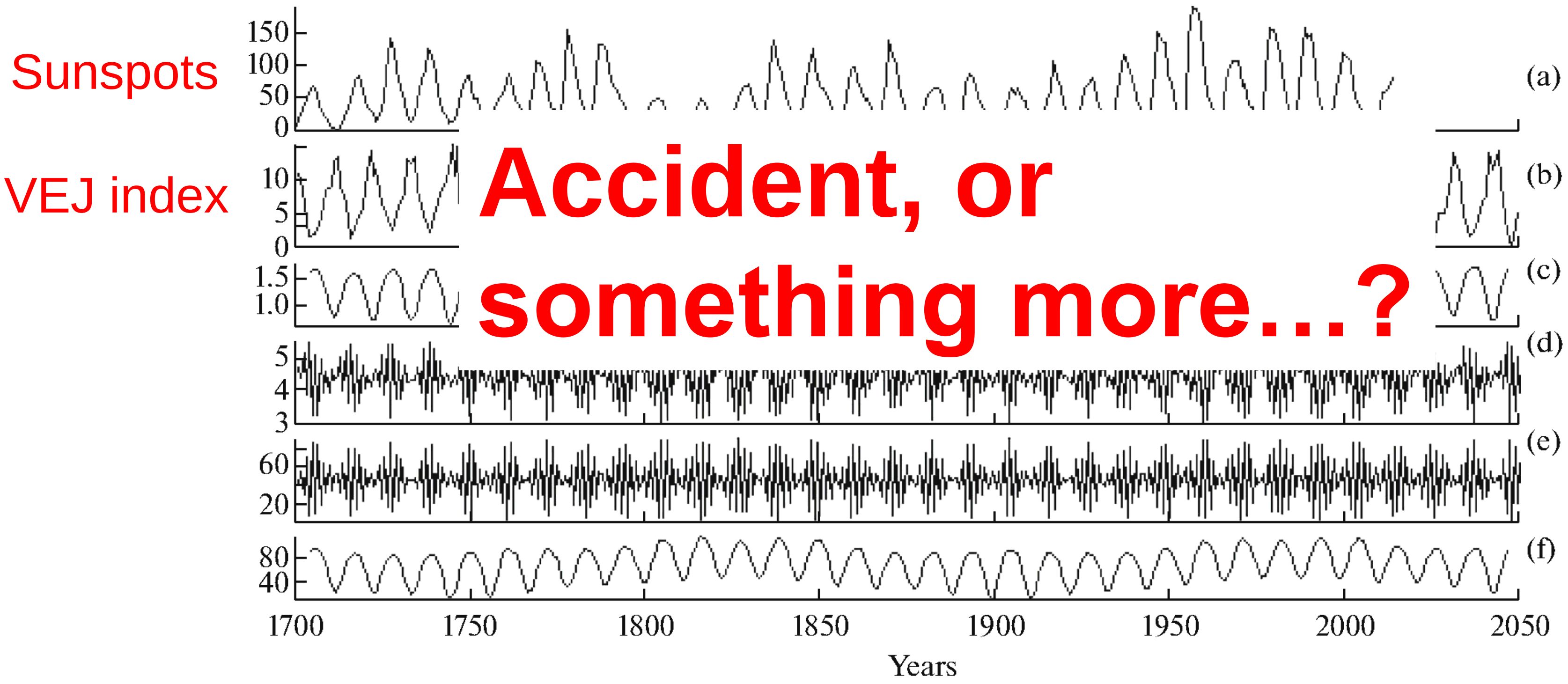

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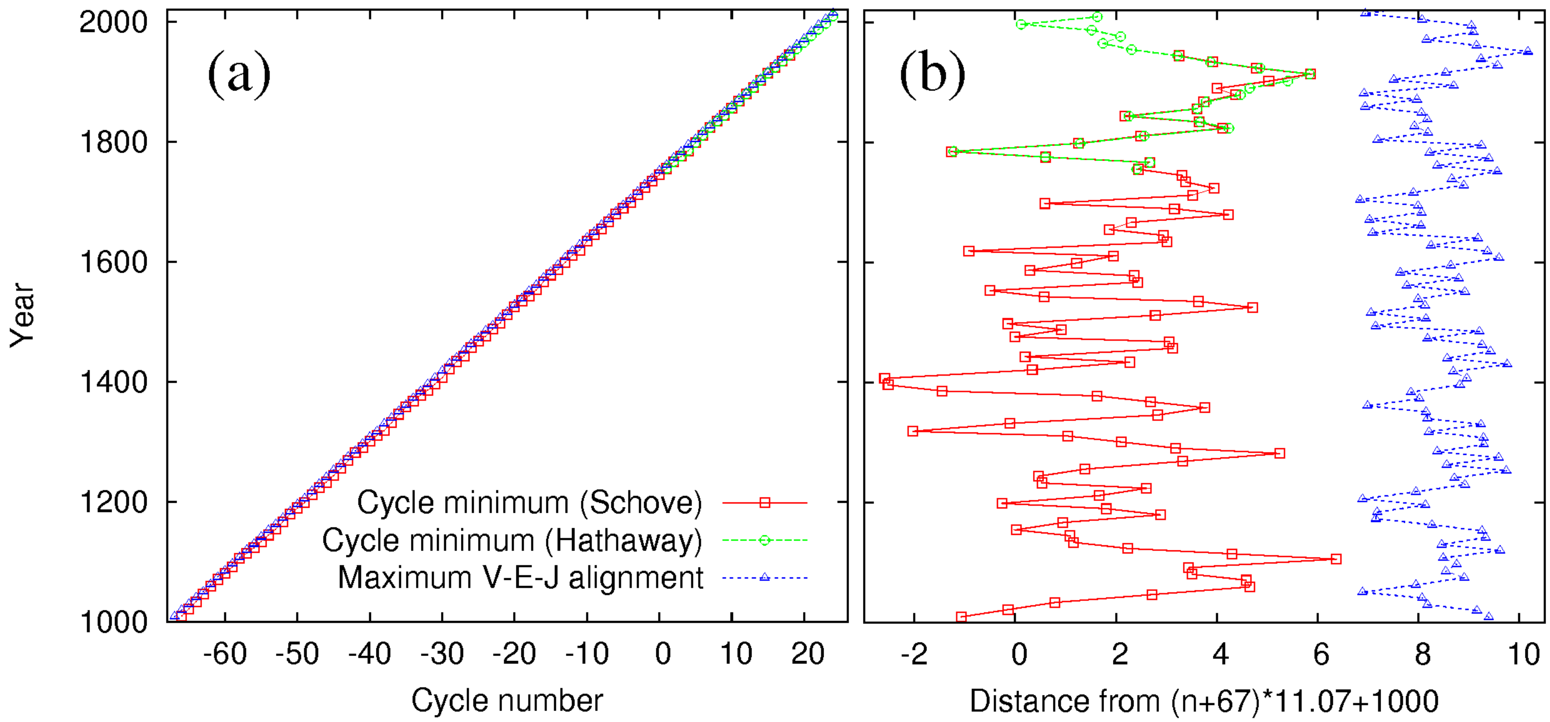
Planetary tides and the solar dynamo: The basic 22 years cycle

Amazing synchronization of solar cycle with the 11.07 years conjunction cycle of the Venus-Earth-Jupiter system (despite tiny tidal forces!)



Schove, D.J.: J. Geophys. Res. 60 (1955), 127; Hathaway, D.H., Liv. Rev. Sol. Phys. 7 (2010), 1; Okhlopkov, Mosc. U. Bull. Phys. B. 71 (2016), 444

Stefani et al., arXiv:1803.08692

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Planetary motion and the solar cycle: Dicke´s argument

Dicke (1978): „No support is found for the conventional view of the sunspot cycle, that there exists a large random walk in the phase of the cycle. Instead, both sunspots and the [D/H] solar/terrestrial weather indicator seem to be paced by an accurate clock inside the sun.“

Is there a chronometer hidden deep in the Sun?

R. H. Dicke
Joseph Henry Laboratories, Physics Department, Princeton University, Princeton, New Jersey 08540

No support is found for the conventional view of the sunspot cycle, that there exists a large random walk in the phase of the cycle. Instead, both sunspots and the [D/H] solar/terrestrial weather indicator seem to be paced by an accurate clock inside the Sun.

IT has long been believed that "the sunspot disturbances, like the eruptions of a geyser, are inherently only roughly periodic"[1]. Observations show a large variation in the ~11 yr

cycle as follows: "It was previously believed that the sunspot cycle resulted from the superposition of different periodic cycles. . . . Since then it has become clear that the rise and fall in the number of spots is due to a number of practically independent individual processes. Thus the idea of a true periodic phenomenon was dropped in favour of the so-called 'eruption hypothesis'. On this hypothesis, each cycle represents an independent eruption of the Sun which takes about 11 yr to die down". This conception of an irregular sunspot cycle, implying a random walk in the phase of the cycle, seems to agree with the Babcock theory and with subsequent modifications of the

Dicke, R.H., Nature 276 (1978), 676

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Planetary motion and the solar cycle: Dicke´s argument reconsidered

Checking Dicke´s argument with Schove´s and Hathaway´s data: Discriminating between a random walk (RW) process and a clocked process (CP) for the years y_n of sunspot maxima (Dicke) or minima (here)

Residuals (phase errors): $\delta y_n = y_n - y_0 - p(n-1)$, p ...average cycle length

A significant discriminating measures is the RATIO of the mean square of δy_n to the mean square of $(\delta y_n - \delta y_{n-1})$

	RATIO	Dicke (N=25)	Here (N=90)
Random walk	$(N+1)(N^2-1)/3(5N^2+6N-3)$	1.72	6.12
Clocked process	$(N^2-1)/2(N^2+2N+3)$	0.46	0.49
Observation		**0.87**	**1.19**

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Planetary motion and the solar cycle: Dicke´s argument reconsidered

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Observation		**0.87**	**1.19**

Can this be sharpened (with better Be or tree ring data) ?

Dicke, R.H., Nature 276 (1978), 676

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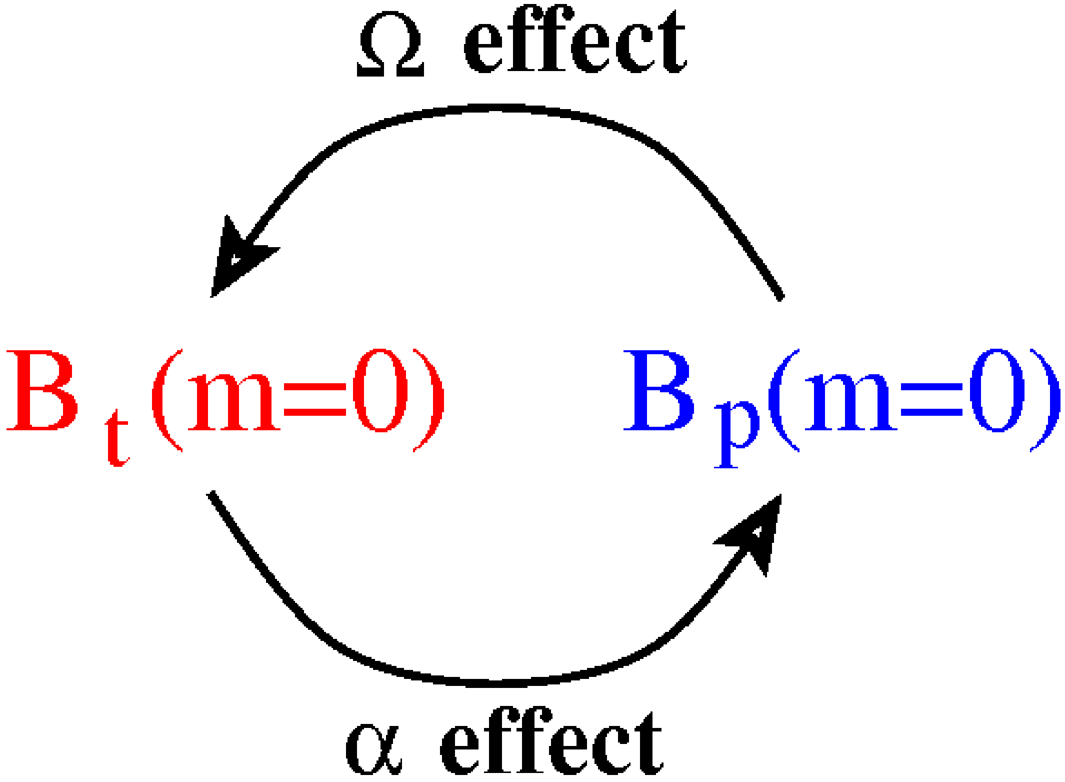
Solar dynamo models
(the main road)

Solar dynamo models: Basics

Any solar dynamo needs:

- some Ω effect to generate toroidal field from poloidal field
- some α effect to regenerate poloidal field from toroidal field



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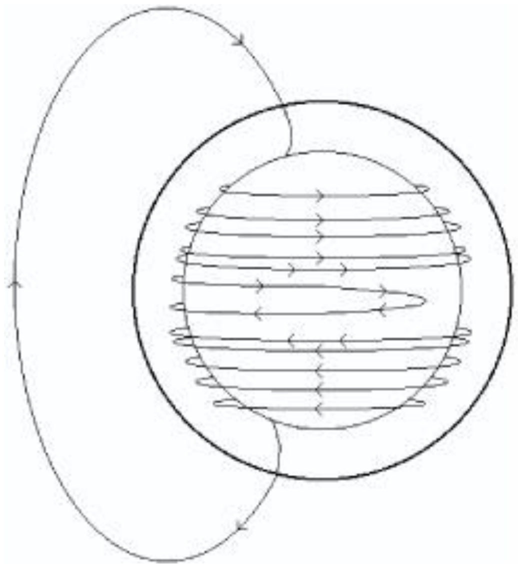
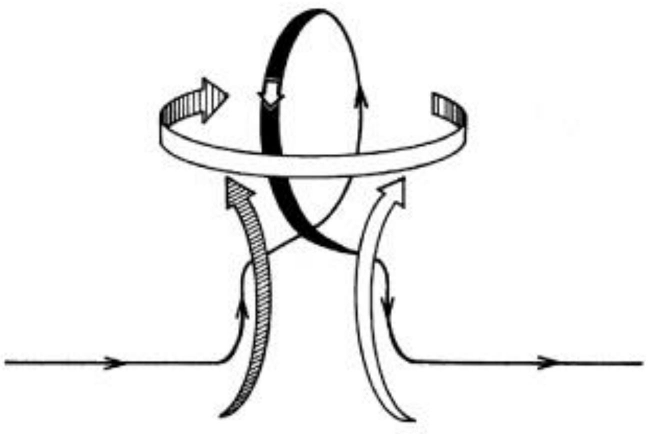


Ω effect



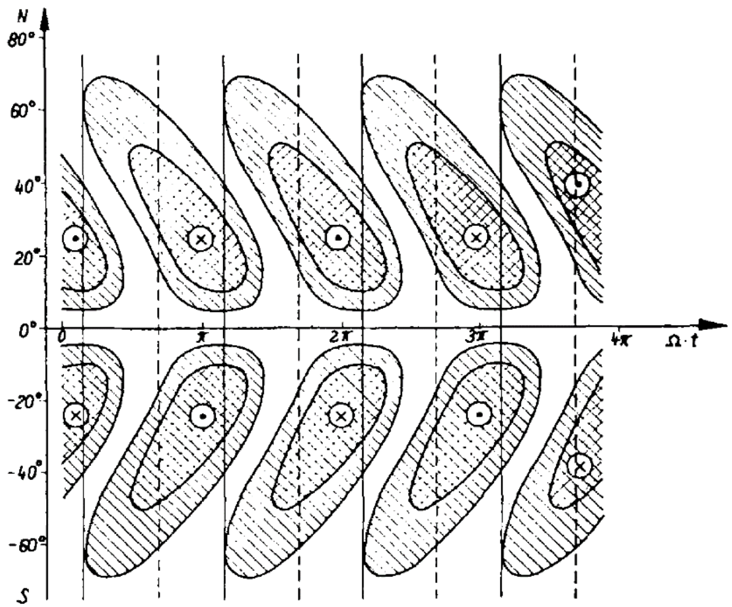
α effect

Solanki et al., Rep. Progr. Phys. 69 (2006), 563

Solar dynamo models: Butterfly diagram of sunspots

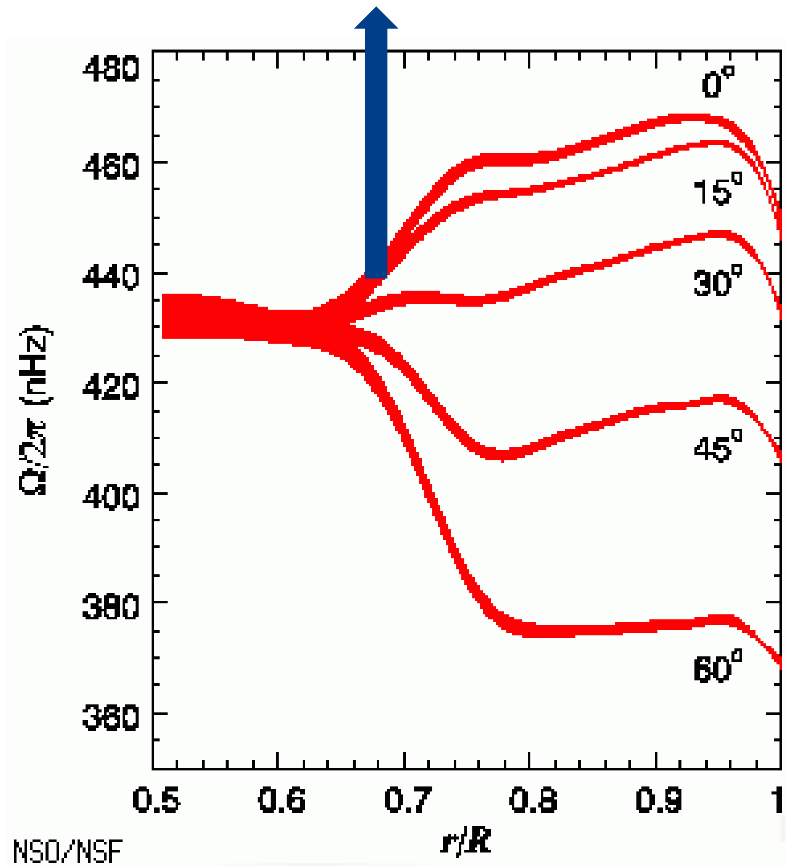
Parker-Yoshimura rule: product of α and $d\Omega/dr$ must be negative to provide the correct butterfly diagram of sunspots

First numerical butterfly diagram for positive α and **negative** $d\Omega/dr$

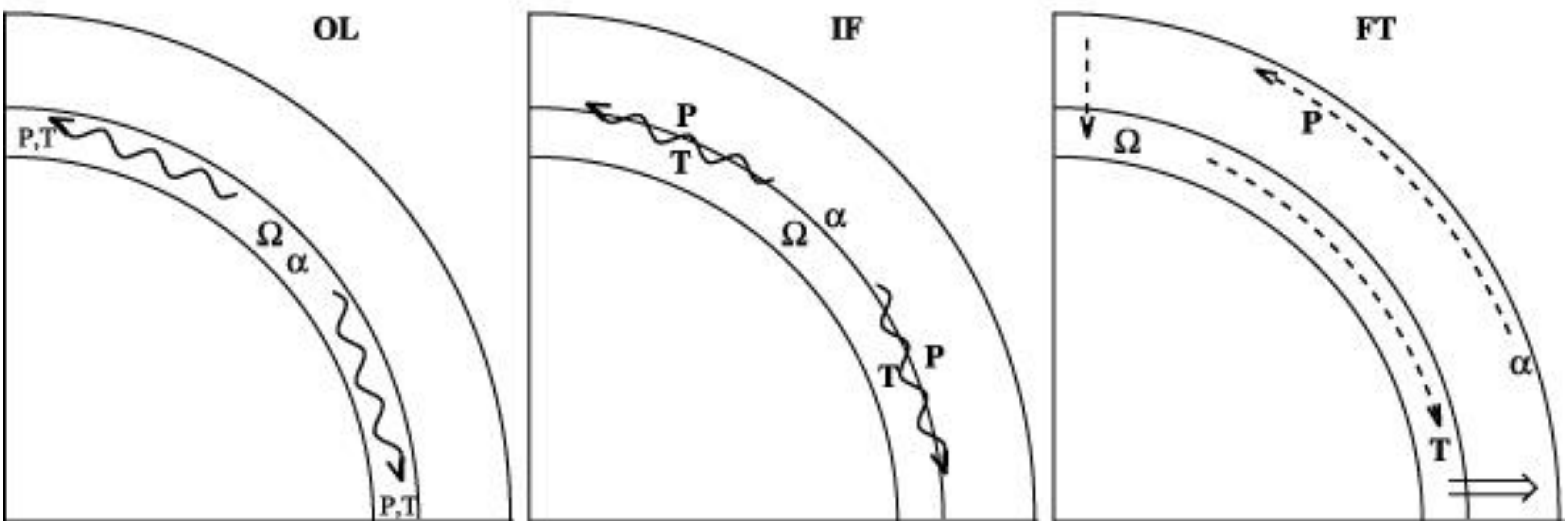


Steenbeck and Krause, Astron. Nachr. 291 (1969), 49

But: helioseismology showed a positive $d\Omega/dr$ in a equator-near strip



Solar dynamo models: possible solutions to Parker-Yoshimura puzzle



Overshoot layer beneath the convection zone

Interface

Flux transport (Babcock-Leighton)

Solanki et al., Rep. Progr. Phys. 69 (2006), 563

Synchronized Babcock-Leighton type dynamos?

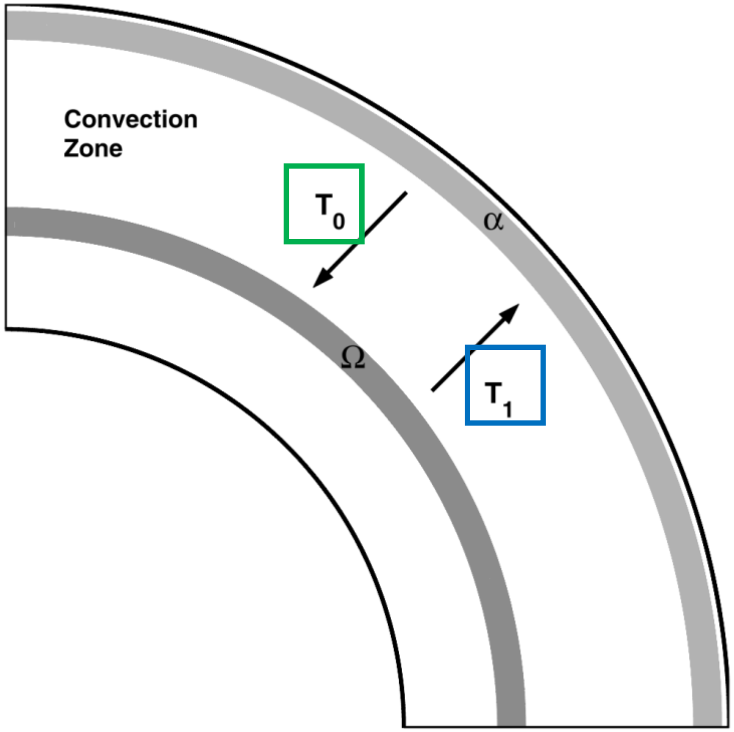
(Motivated by Antonio´s idea!)

Basis: A time-delay model emulating a Babcock-Leighton dynamo

Wilmot-Smith et al., Astrophys. J. 652 (2006), 696

$$\dot{A}(t) = \alpha(t - T_1)B(t - T_1) - \tau^{-1}A(t)$$

$$\dot{B}(t) = \Omega A(t - T_0) - \tau^{-1}B(t)$$



T_1 Time delay for toroidal field transport

T_0 Time delay for poloidal field transport

$$\alpha(t) = \frac{\alpha_0}{4}[1 + \text{erf}\,(B^2(t) - B^2{}_{Min})][1 - \text{erf}\,(B^2(t) - B^2{}_{Max})]$$

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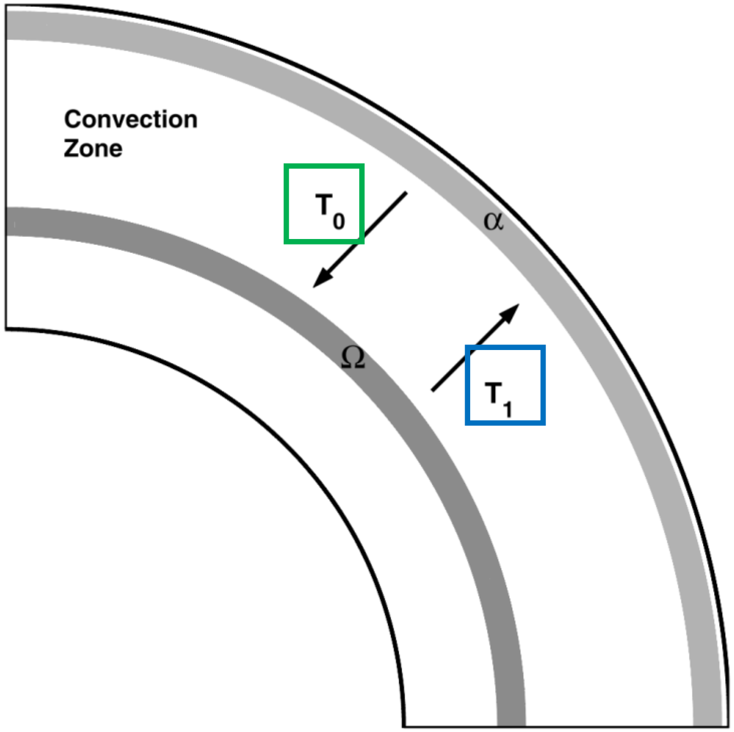

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NEW: Considering Ω(t) or B_{Min}(t) as time-dependent

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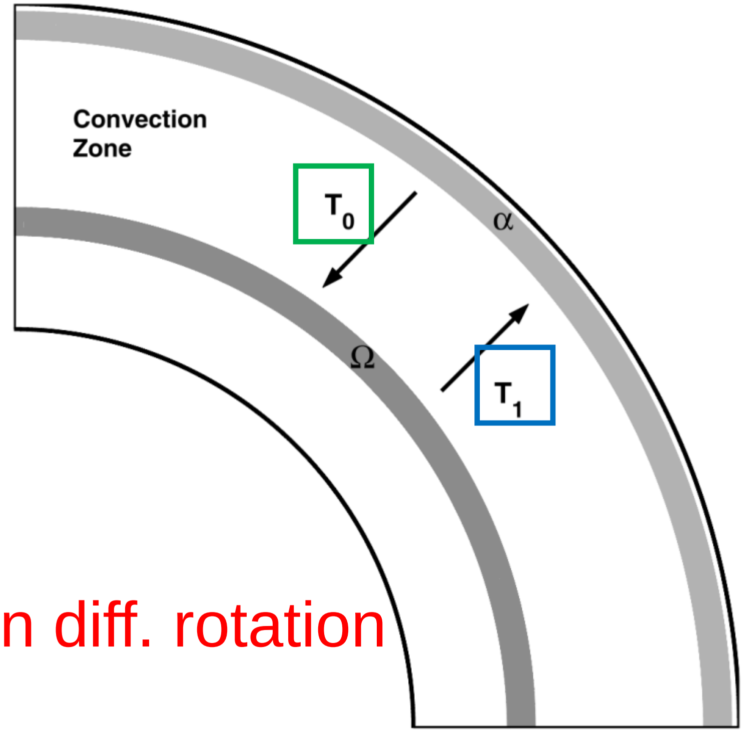
Wilmot-Smith et al., Astrophys. J. 652 (2006), 696



$$\dot{A}(t) = \alpha(t - T_1) B(t - T_1) - \tau^{-1} A(t)$$

$$\dot{B}(t) = \Omega(t) A(t - T_0) - \tau^{-1} B(t)$$

Ω(t) emulates putative tidal influence on diff. rotation

$$\alpha(t) = \frac{\alpha_0}{4} [1 + \mathrm{erf}\,(B^2(t) - B^2_{Min}(t))][1 - \mathrm{erf}\,(B^2(t) - B^2_{Max})]$$

B_{Min}(t) emulates a varying flux storing capacity of the tachocline due to **high sensitivity of sub-adiabaticity** on tidal forcing (idea of Antonio Ferriz Mas)

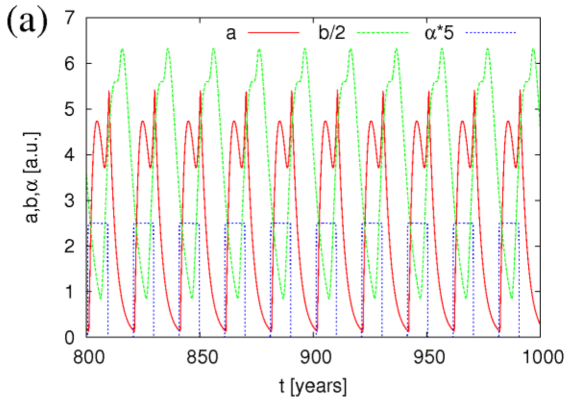
Numerical parameter studies

	Flux-transport dominated $\tau>T_0+T_1$	Diffusion dominated $\tau<T_0+T_1$	Intermediate regime $T_1<\tau<T_0$
$\alpha\Omega>0$	(sawtooth-shaped) pulsations	(sawtooth-shaped) pulsations	(sawtooth-shaped) pulsations
$B_{Min}(t)= B_0(1+a \sin(2\pi t/11.07)$	No synchronization	No synchronization	No synchronization
$\Omega(t)= B_0(1+a \sin(2\pi t/11.07)$	No synchronization	No synchronization	**Synchronization (only for large a)**
$\alpha\Omega<0$	(sawtooth-shaped) oscillations	(complicated) oscillations	(sawtooth-shaped) oscillations
$B_{Min}(t)= B_0(1+a \sin(2\pi t/11.07$	No synchronization	No synchronization	No synchronization
$\Omega(t)= B_0(1+a \sin(2\pi t/11.07)$	No synchronization	No synchronization	**Synchronization (only for large a)**

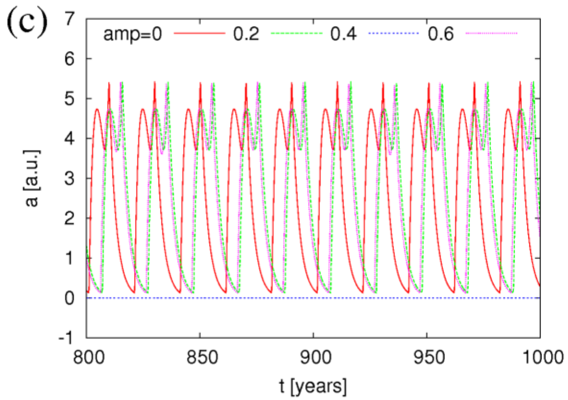
Stefani et al., Solar Physics 291 (2018), 12

Example: Intermediate regime $T_1<t<T_0$, $\alpha\Omega>0$, Pulsations

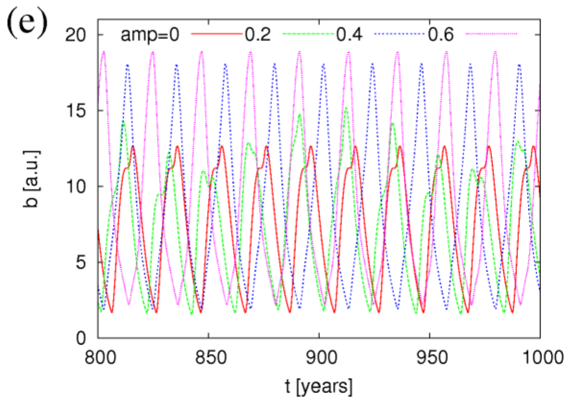
Unperturbed B_{Min} and Ω

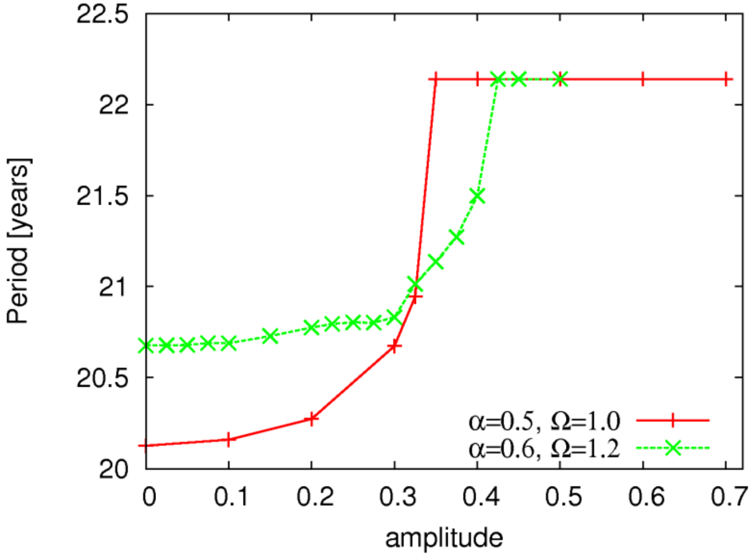


Perturbed $B_{min}(t)$ with a $\sin(2\pi t/11.07)$



Perturbed Ω (t) with a $\sin(2\pi t/11.07)$





Synchronization, but only for unrealistically large a

Example: Intermediate regime $T_1<t<T_0$, $\alpha\Omega<0$, Oscillations

Unperturbed

B_{Min} and Ω

Perturbed

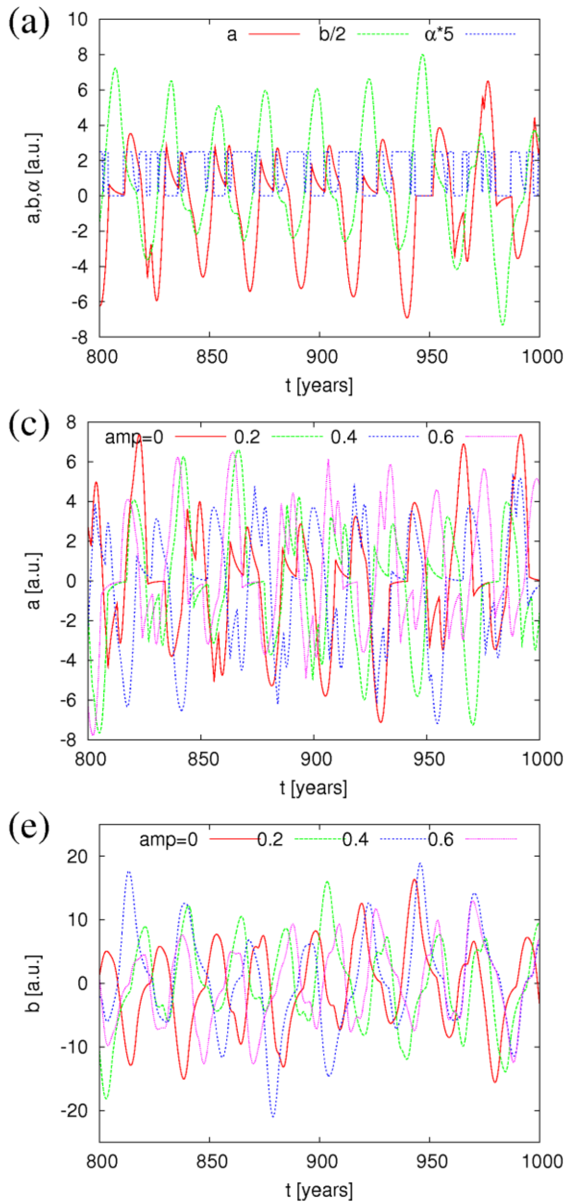
$B_{min}(t)$ with

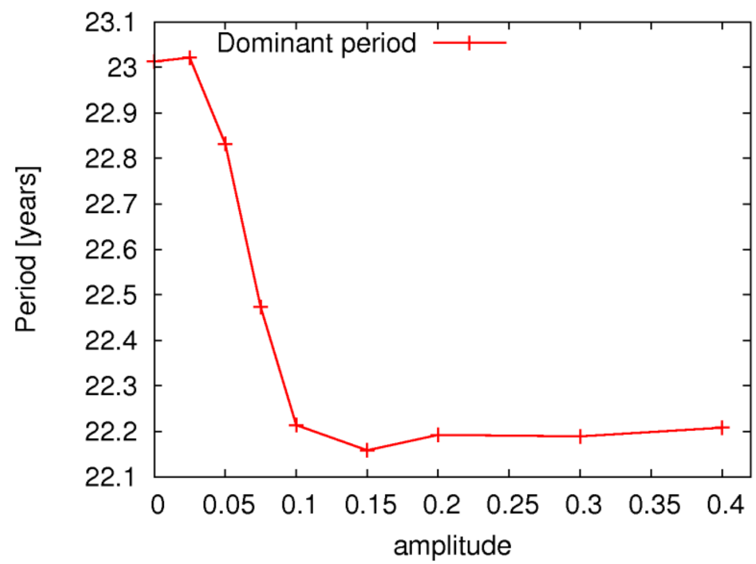
a $\sin(2\pi t/11.07)$

Perturbed

Ω (t) with

a $\sin(2\pi t/11.07)$





A sort of synchronization, but only for large a

Tayler-Spruit dynamo and the helicity question

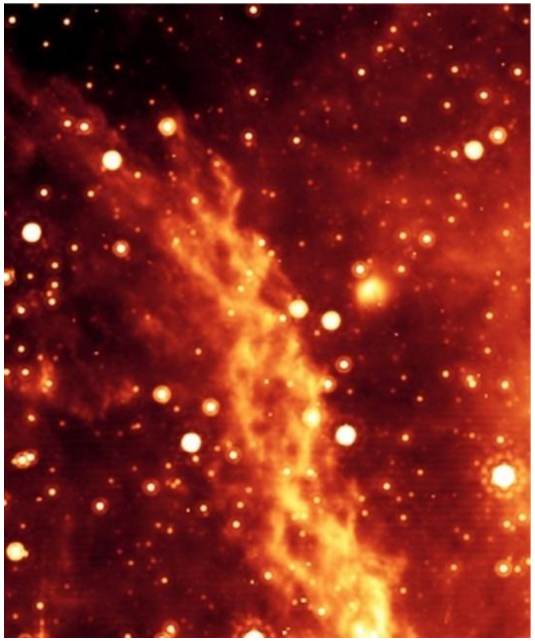
Kink-type Tayler instability (TI) at low Pm

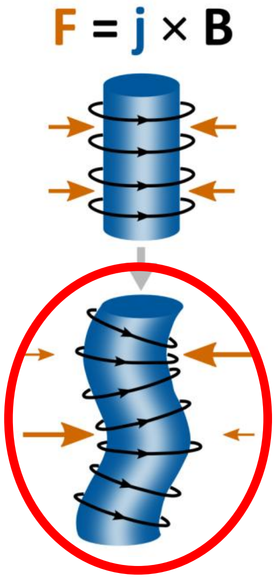
Astrophysical motivation:

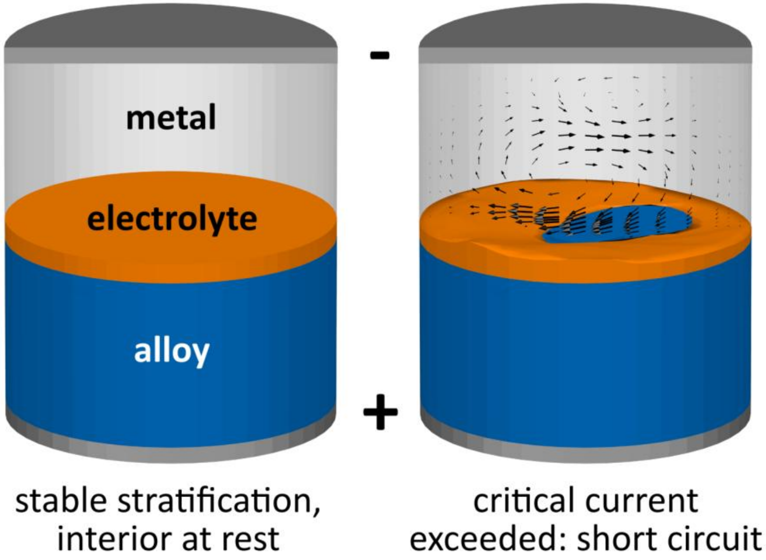
- Alternative mechanism of solar dynamo (Tayler-Spruit dynamo)
- Structure formation in cosmic jets

Technical motivation:

- Understanding and controlling the complex MHD of liquid metal batteries



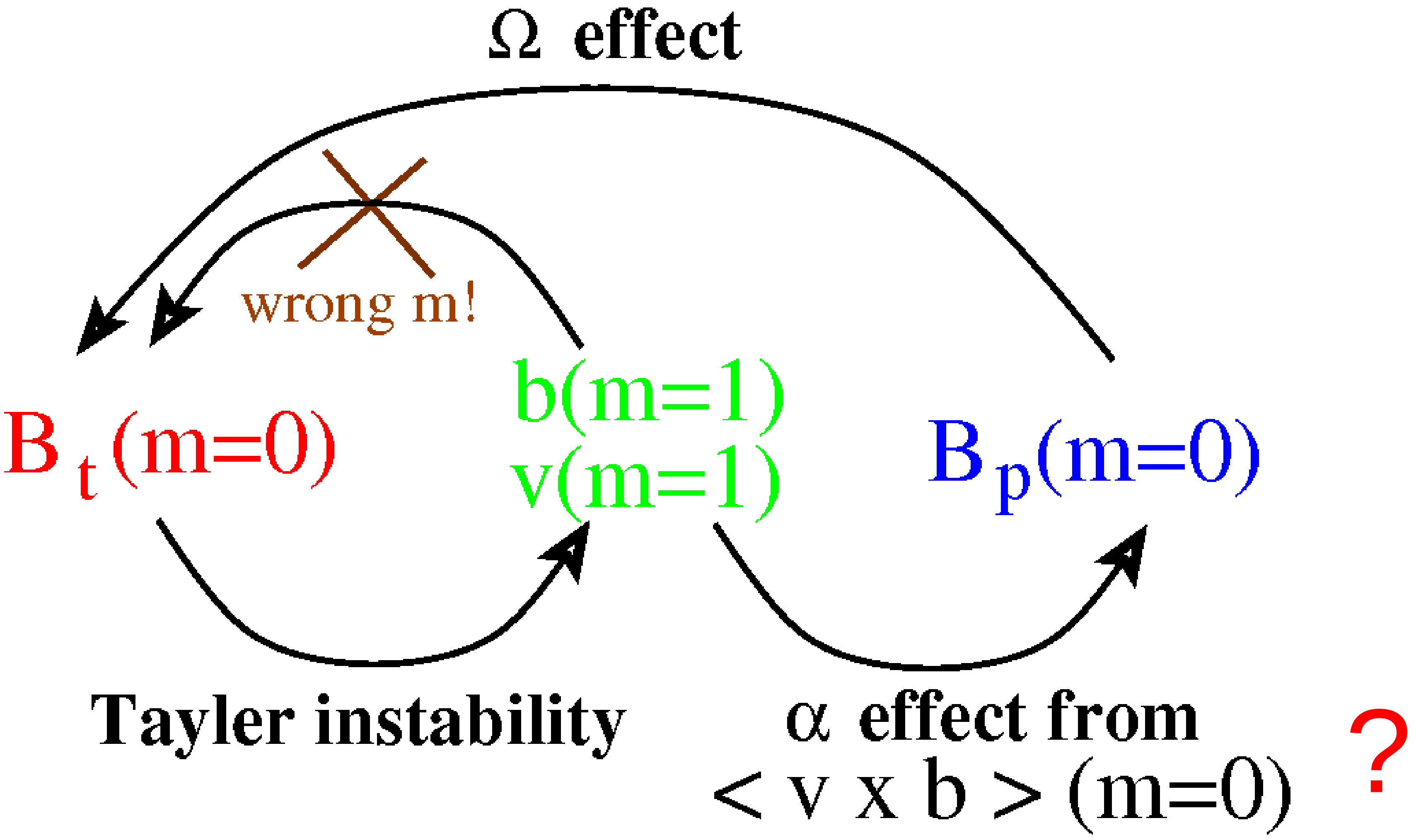




Stefani et al., Energy Conv. Managem. 52 (2011), 2982;

Weber et al., J. Power Sources 265 (2014), 166

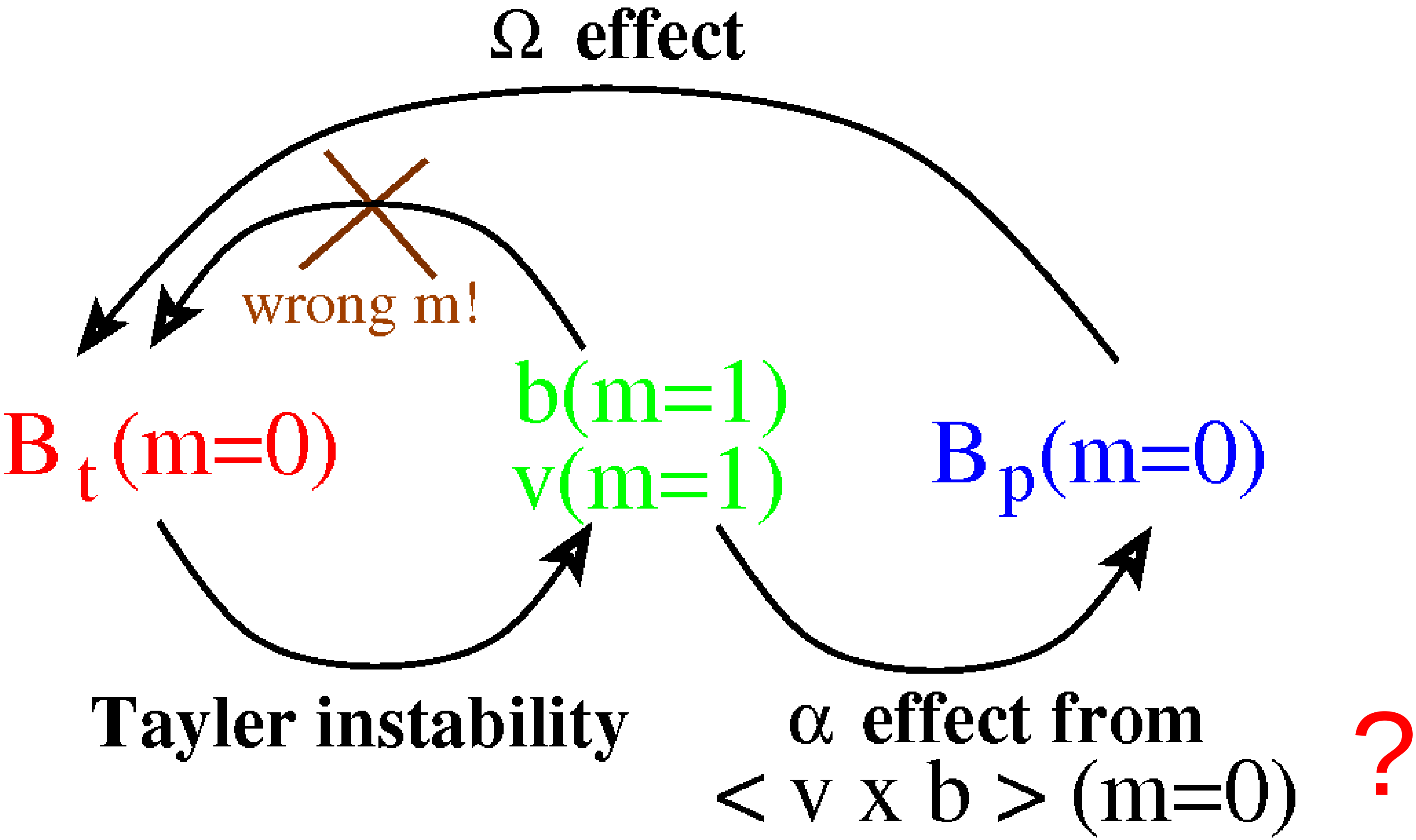
Tayler-Spruit dynamo: the main problem



Spruit, Astron. Astrophys. 381 (2002) 923;

Zahn et al., Astron. Astrophys. 474 (2007) 147

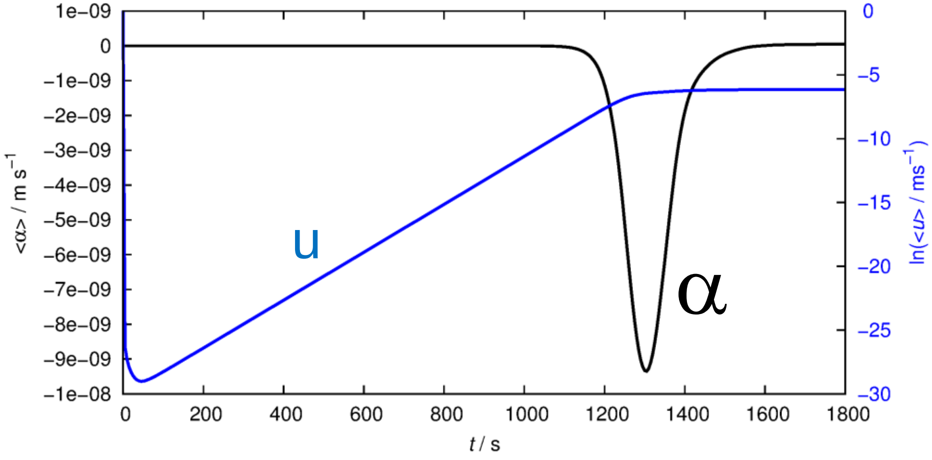
Tayler-Spruit dynamo: the main problem

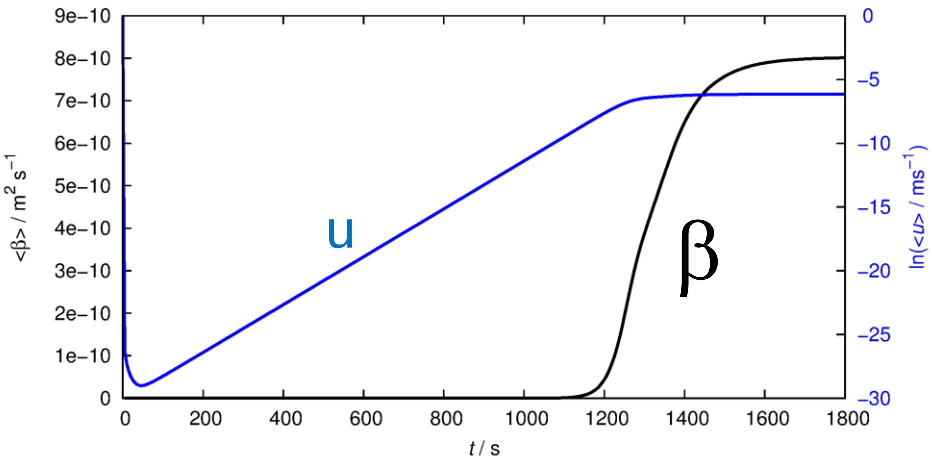


See Ferriz Mas, Schmitt, Schüssler, Astron. Astrophys. 289 (1994), 949 for fluxtube picture

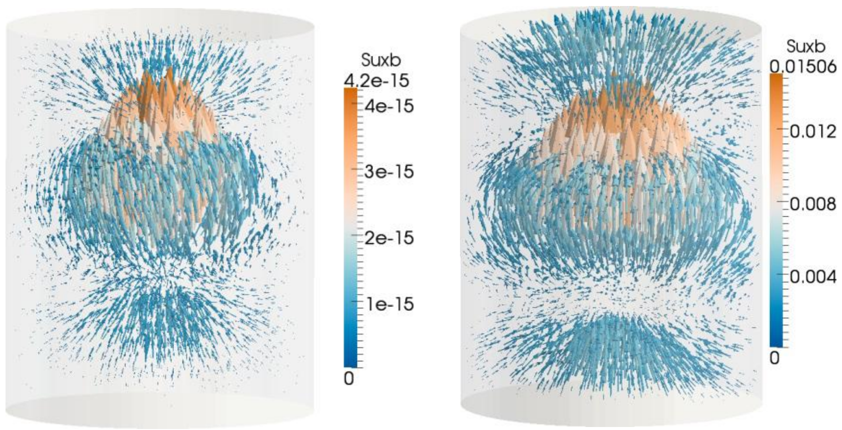
Tayler-Spruit dynamo: Any helical symmetry breaking at low Pm ?

At low Pm, neither the β effect nor the α effect are strong enough to change the magnetic base configuration. α effect appears only in the exponential growth phase and disappears in the saturation regime.





Induced current at…



500 s 1800 s

Example: h/d=1.25, Ha=55

Weber et al., New J. Phys. 17 (2015), 113013

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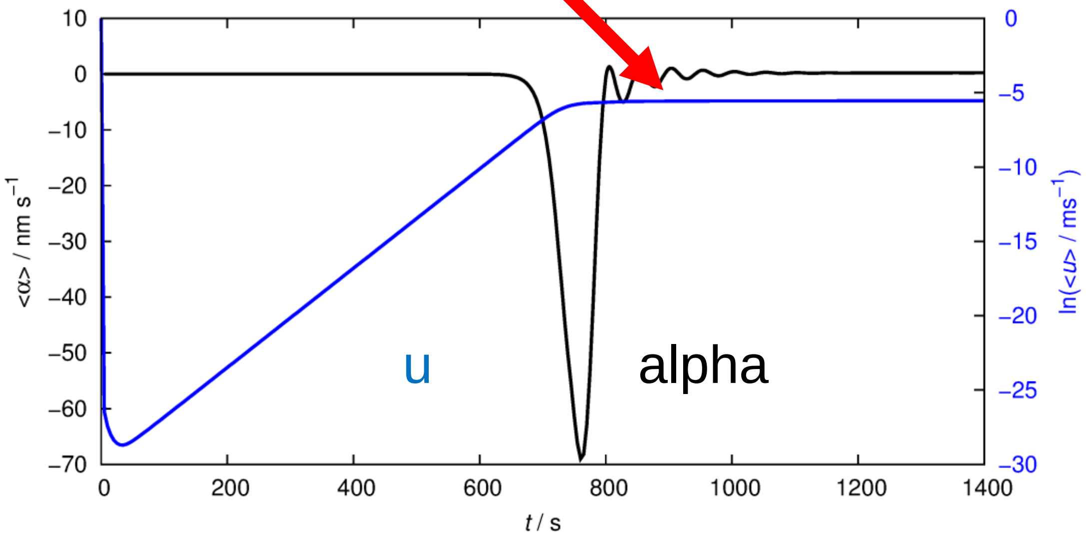
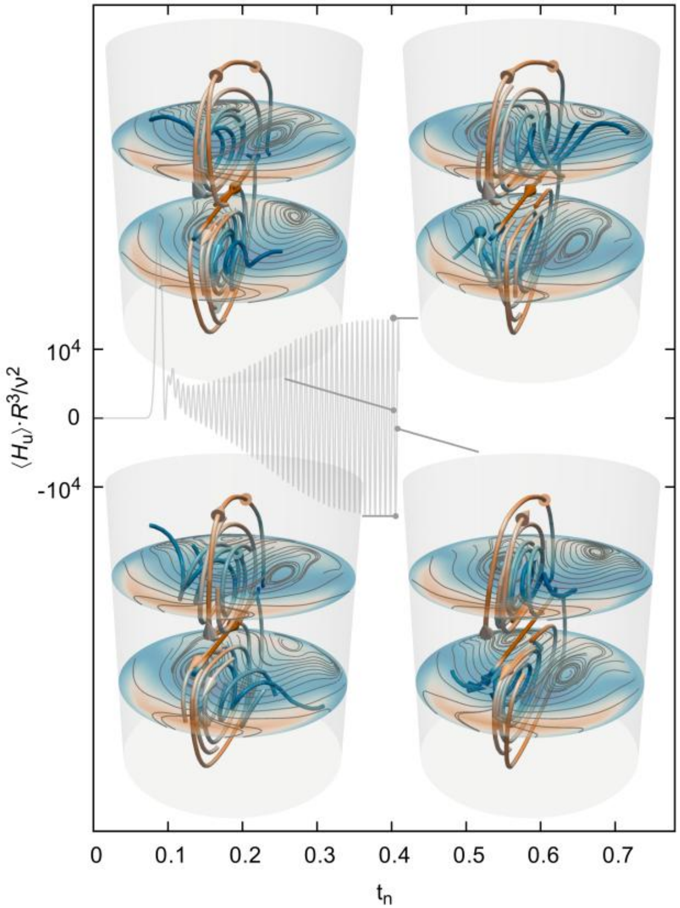
Tayler-Spruit dynamo: Saturation and helicity oscillations at Pm=10^{-6}

(Damped) helicity oscillations Ha =70

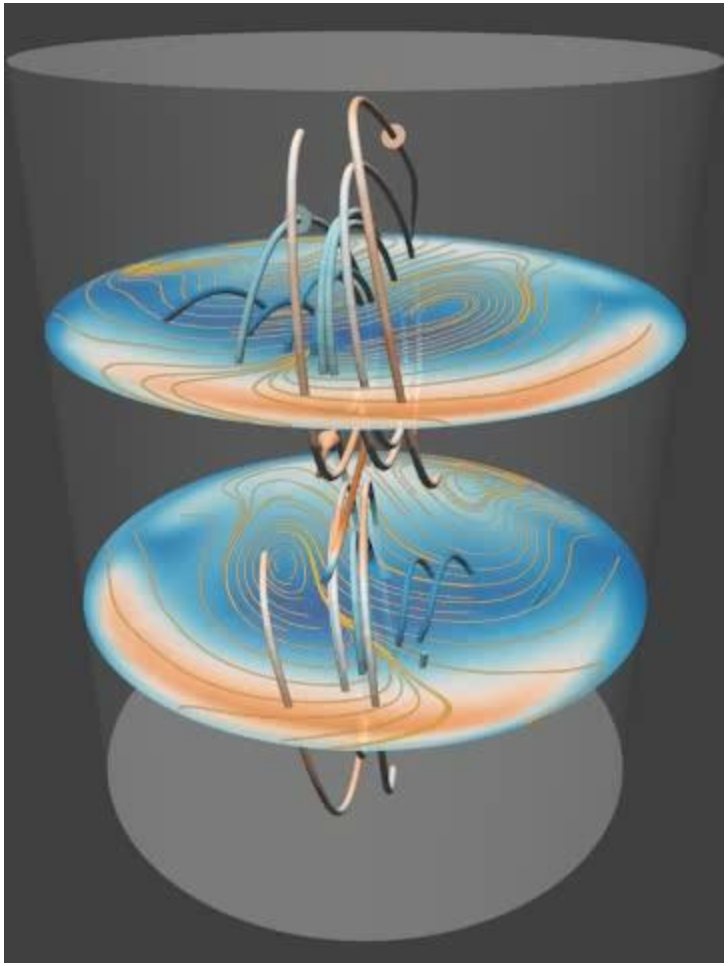




Ha =100

Weber et al., New J. Phys. 17 (2015), 113013

Tayler-Spruit dynamo: Character of the helicity oscillations



Ha =100
Pm=10^{-6}

Weber et al., New J. Phys. 17 (2015), 113013

Resonant excitation of helicity oscillations

Resonant excitation of helicity oscillations

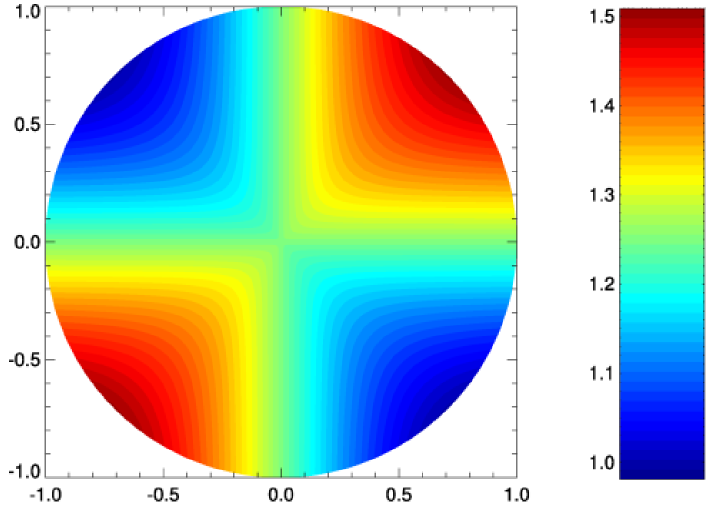
Tayler-Spruit-like dynamo:

• Ω-effect due to differential rotation

• α-effect relies on chiral symmetry breaking

• α-oscillation could be triggered and **synchronized** by planetary torques (emulated here by a m=2 viscosity oscillation) **with very low energy input**

m=2 viscosity perturbation



$$\nu(r,\phi,t) = \nu_0\{1 + A[1 + 0.5 r^2 / R^2 \sin(2\phi)(1 + \cos(2\pi t / T_\nu))]\}$$

Amplitude A

Stefani et al, Solar Phys. 291 (2016), 2197; arXiv:1511.09335

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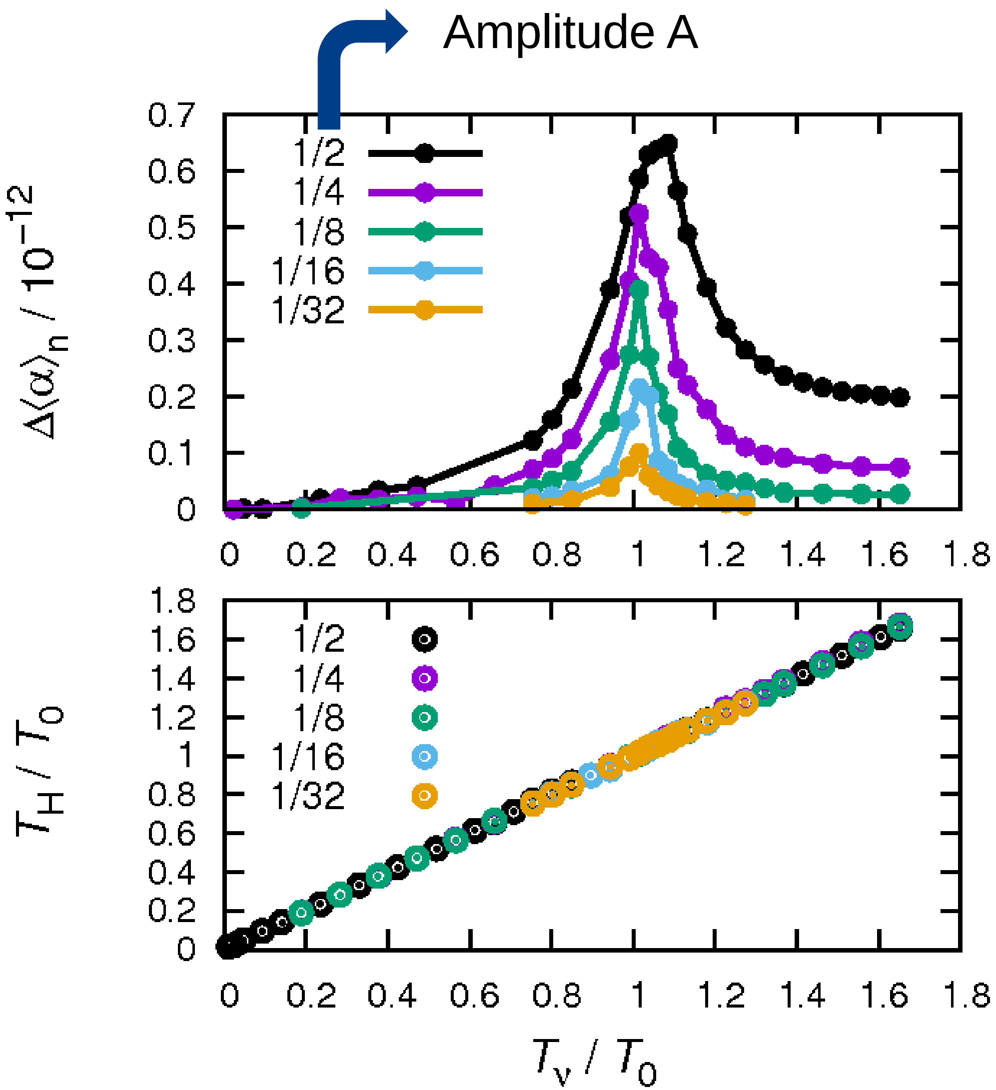
Resonant excitation of helicity oscillations



Amplitude of α oscillations in dependence on the ratio of the period of the m=2 viscosity oscillation to the period of intrinsic helicity oscillations

Period of α oscillations shows 1:1 resonance.

DRESDEN concept

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A simple, and a slightly more complicated model of a synchronized dynamo

A simple model of a synchronized dynamo

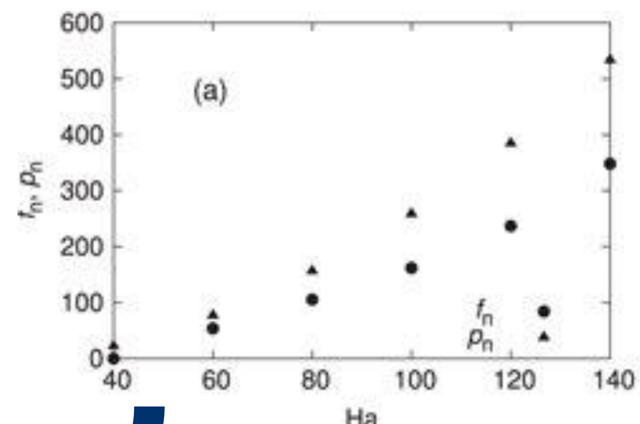
$$\dot{A}(t) = \alpha(t)B(t) - \tau^{-1}A(t)$$

$$\dot{B}(t) = \omega A(t) - \tau^{-1}B(t)$$

$$\alpha(t) = \frac{c}{1+gB^2(t)} + \frac{pB^2(t)}{1+hB^4(t)}\sin(2\pi t/T_\nu)$$

Constant α term with quenching

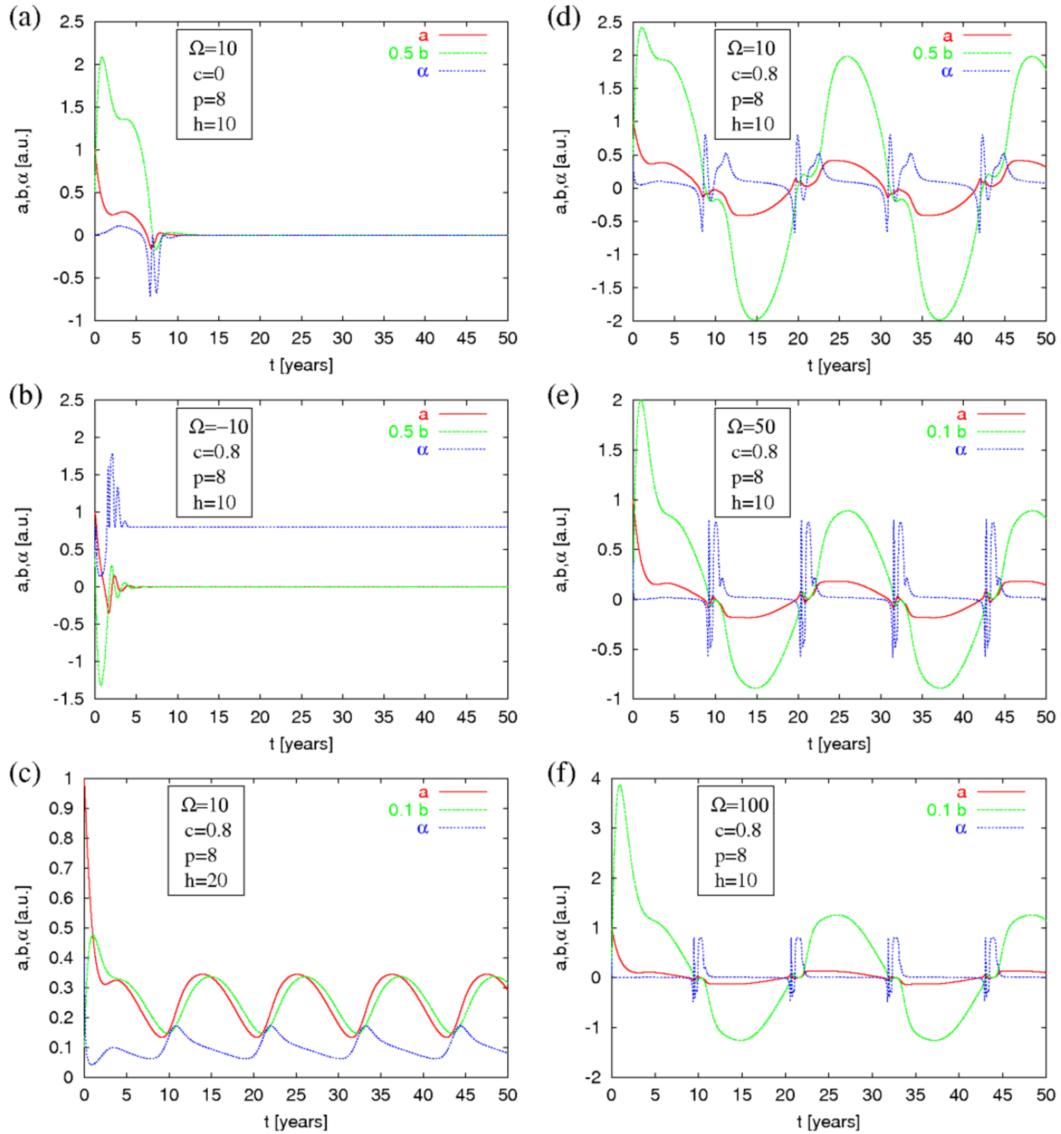
Oscillating α term with resonant dependence on the field strength (i.e., on the frequency of helicity oscillations)



Stefani et al, Solar Phys. 291 (2016), 2197; arXiv:1511.09335

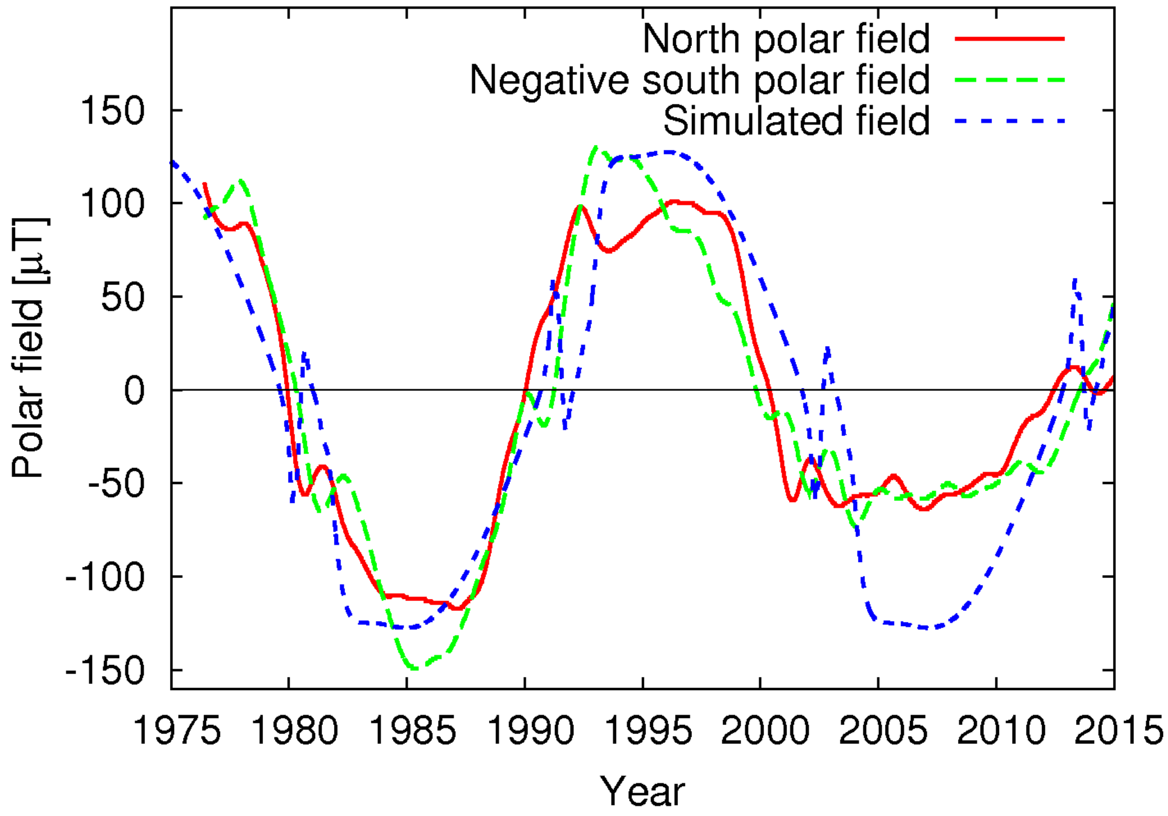
A simple model of a synchronized dynamo

For a wide range of parameters, a robust 22.14 years Hale cycle appears…

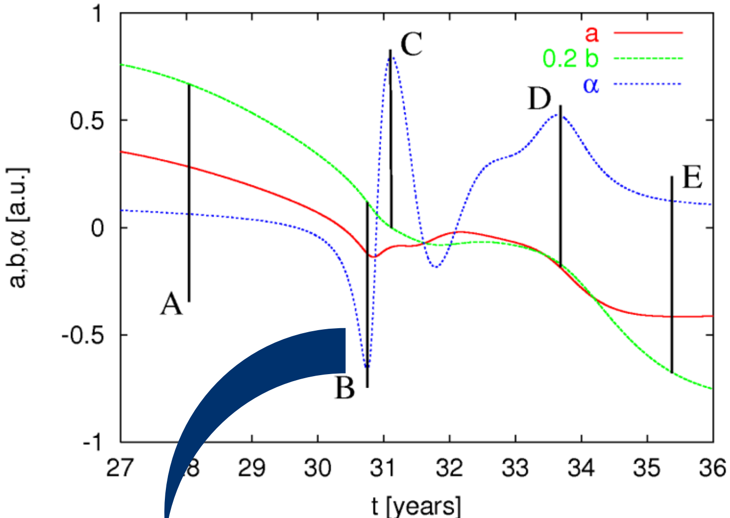


A simple model of a synchronized dynamo

Comparison with measured polar field shows interesting „mid-term oscillations“

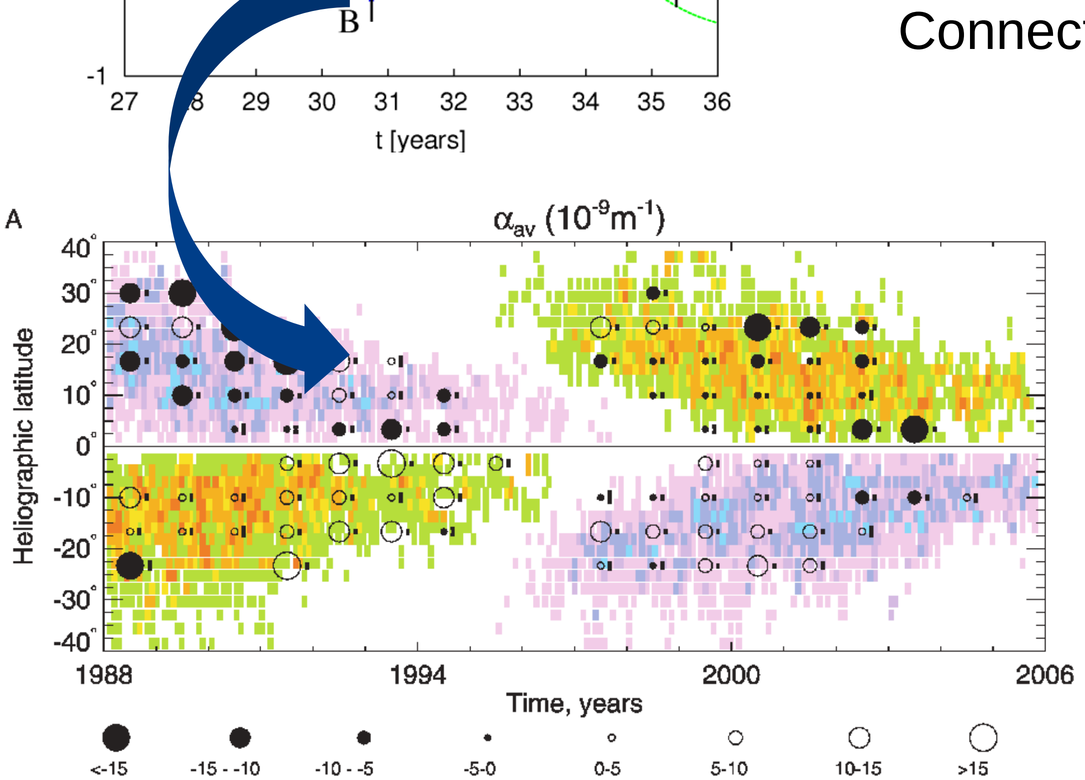


A simple model of a synchronized dynamo: „wrong“ helicities?



α acquires the „wrong“ sign for a short period before the field reversal

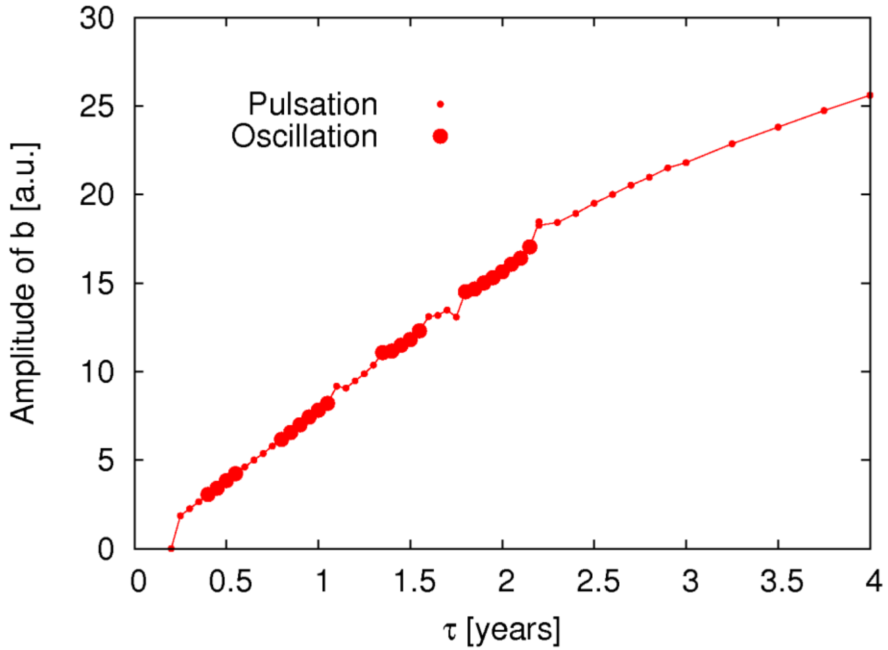
Connection with observation?



Zhang et al., MNRAS 402 (2010), L30

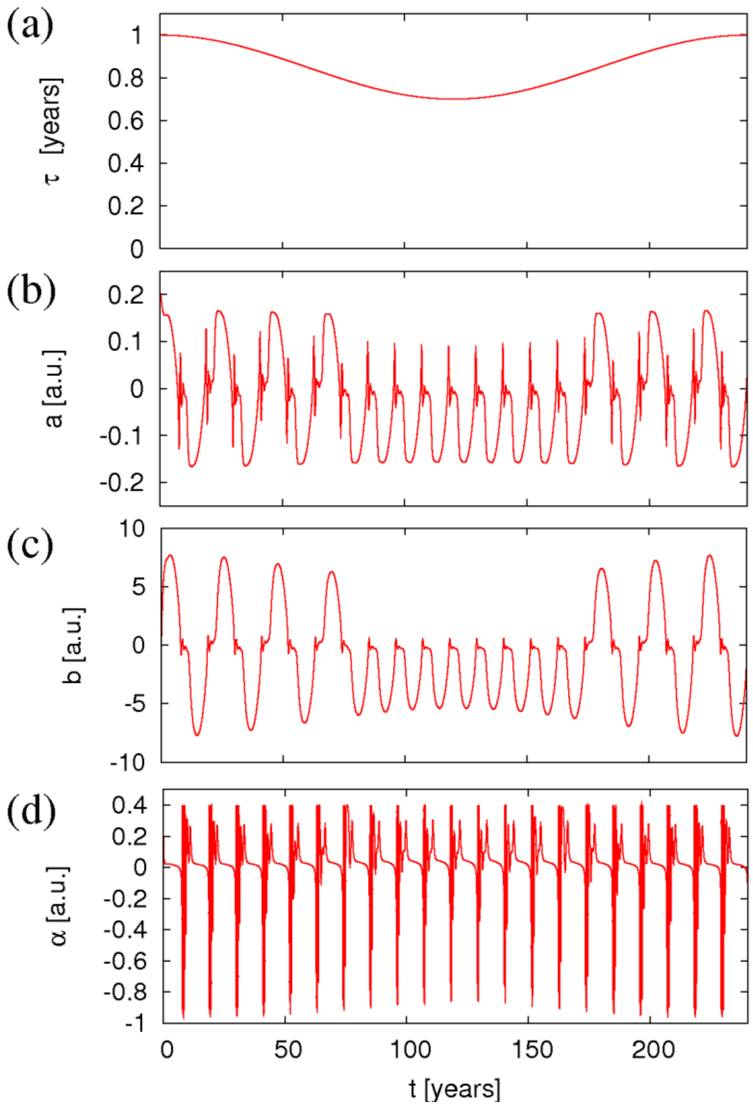
Transitions between oscillations and pulsations → „Grand minima“ ?

Bands of oscillations and pulsations



„Grand minima“ with phase coherence?

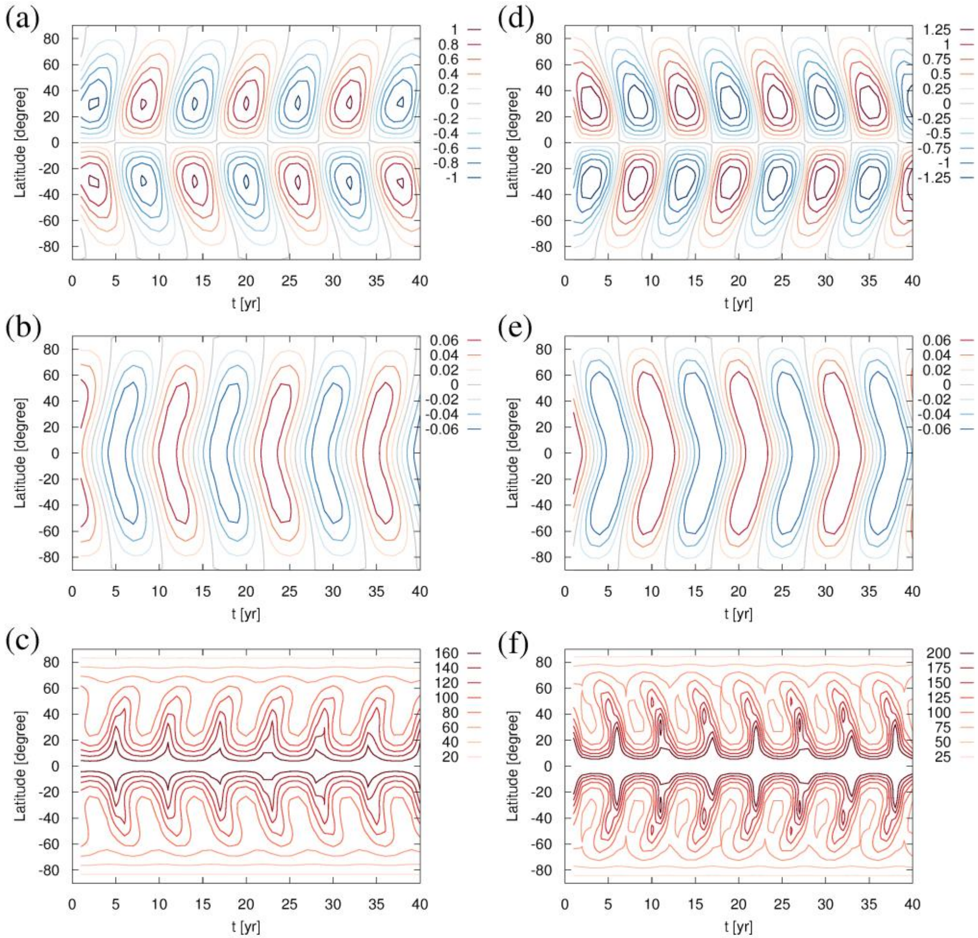
Stefani et al., arXiv:1706.07638



First results with a 1D-model: Test case with Ω-quenching

α=-1, τ=1

ω_0=170 ω_0=250



$$\frac{\partial B(\theta,t)}{\partial t} = \omega(\theta,t)A(\theta,t) - \frac{1}{\tau}\frac{\partial^2 B(\theta,t)}{\partial \theta^2}$$
$$\frac{\partial A(\theta,t)}{\partial t} = \alpha(\theta,t)B(\theta,t) - \frac{1}{\tau}\frac{\partial^2 A(\theta,t)}{\partial \theta^2},$$

$B(\theta,t)$

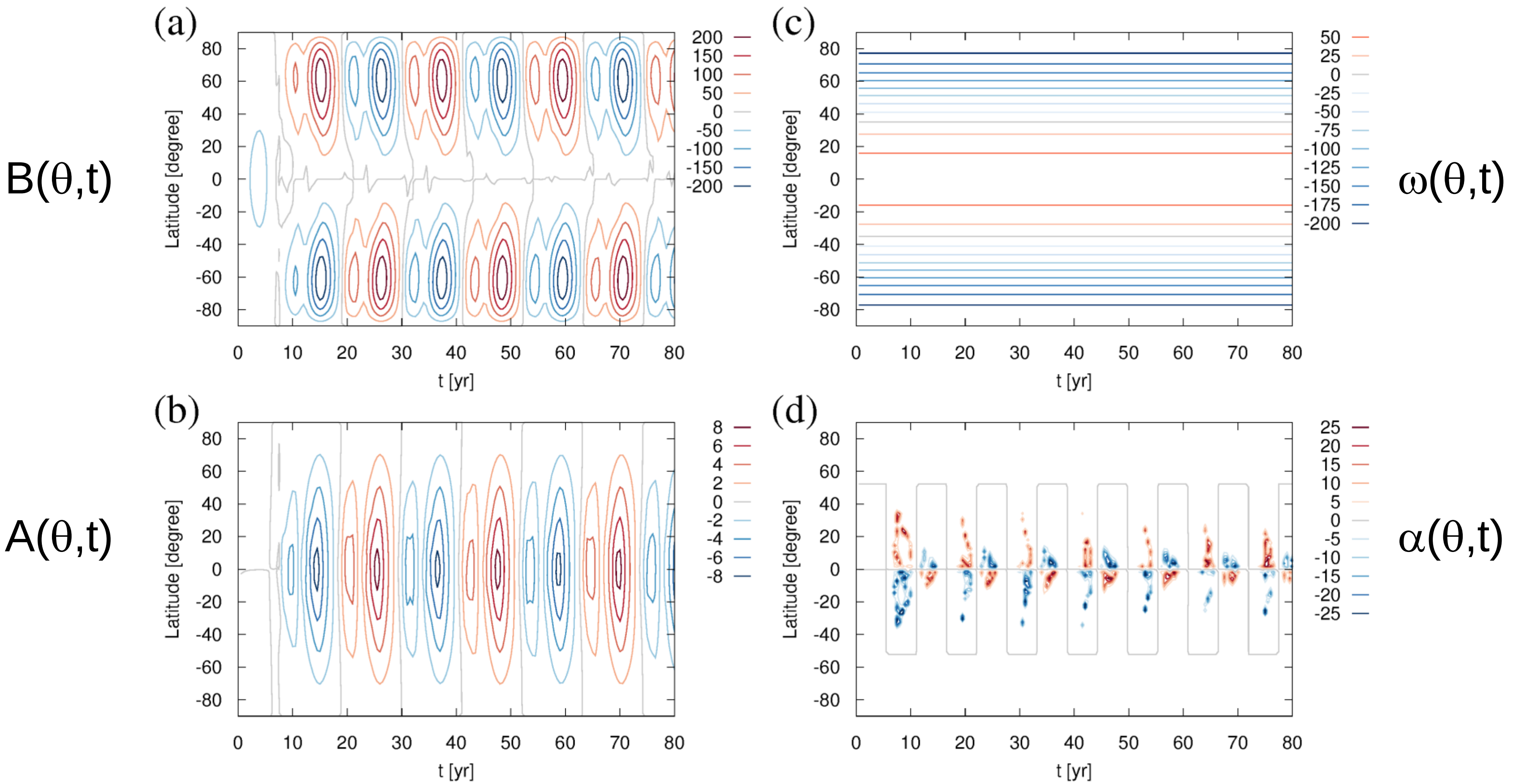
$A(\theta,t)$

$\omega(\theta,t)$

Stefani et al., arXiv:1803.08692

First results with a 1D-model: Test case with resonant and periodic α

$\omega(\theta,\tau)=\omega_0(1\text{-}0.939\text{-}0.136\cos^2(\theta)\text{-}0.1457\cos^4(\theta))$, $\omega_0=1000$, $\tau=2$, $\alpha_{periodic}=60$



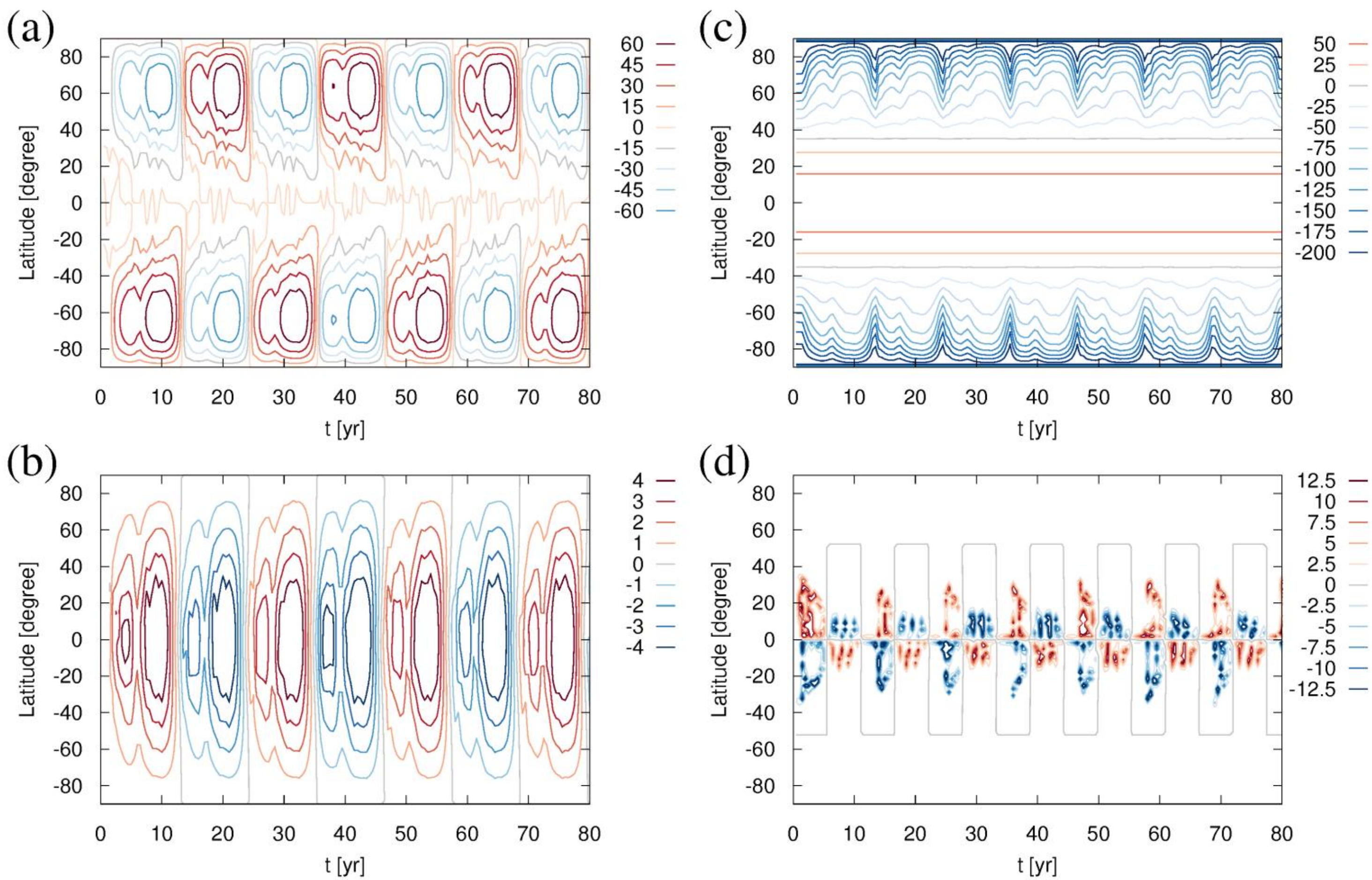
Stefani et al., arXiv:1803.08692

First results with a 1D-model: Test case with resonant and periodic α

ω_0=1000, τ=2, $\alpha_{periodic}$=40 + quenching of ω (or σ) in the pole-near regions

B(θ,t) | $\omega(\theta$,t)

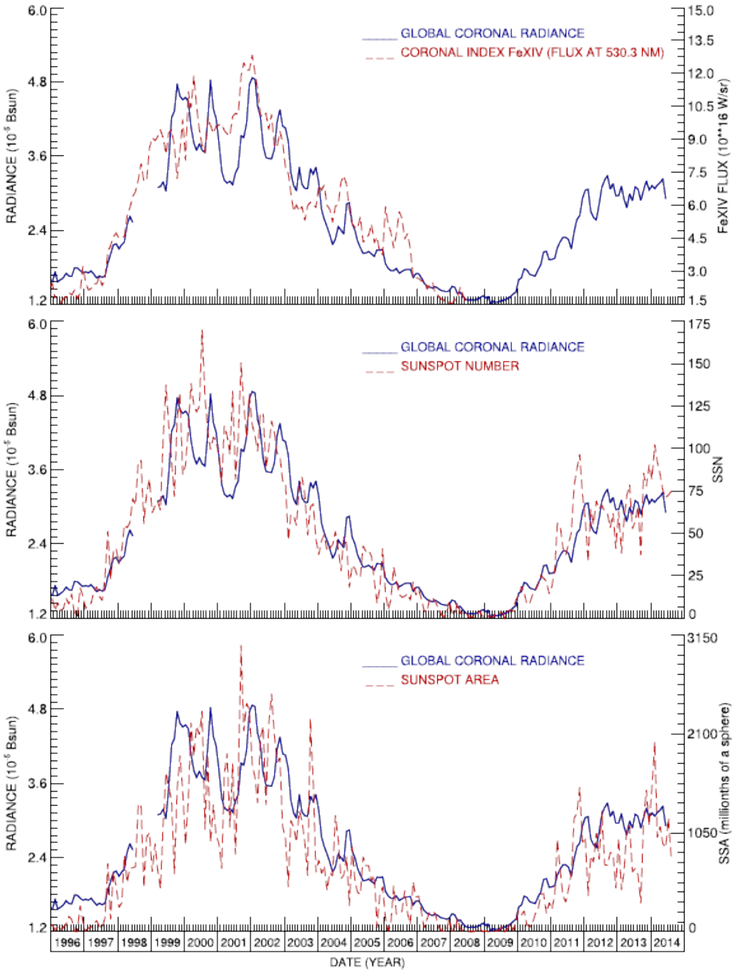
A(θ,t) | $\alpha(\theta$,t)

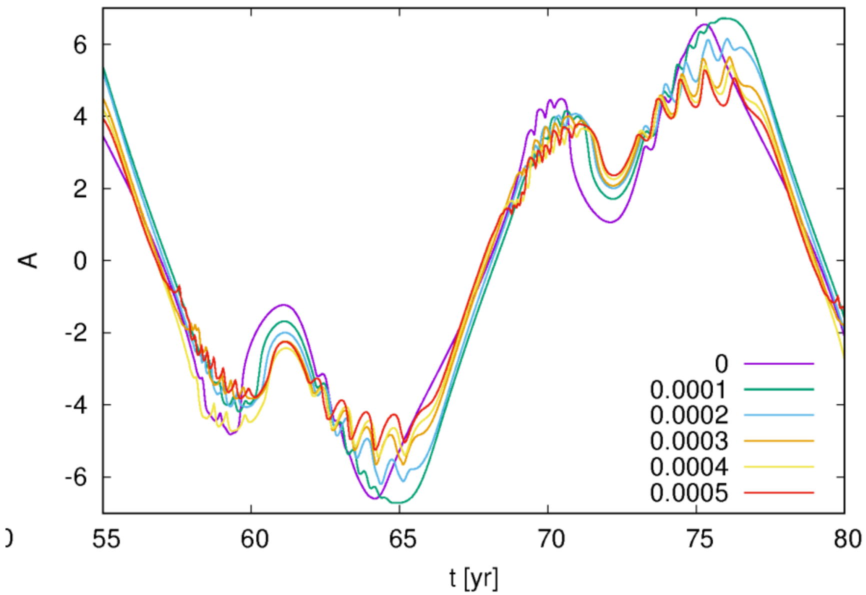


Stefani et al., arXiv:1803.08692

Some interesting features: Mid-term oscillations

Mid-term oscillations (~1.7 years), as visible in many solar data, appear naturally in the synchronization model…

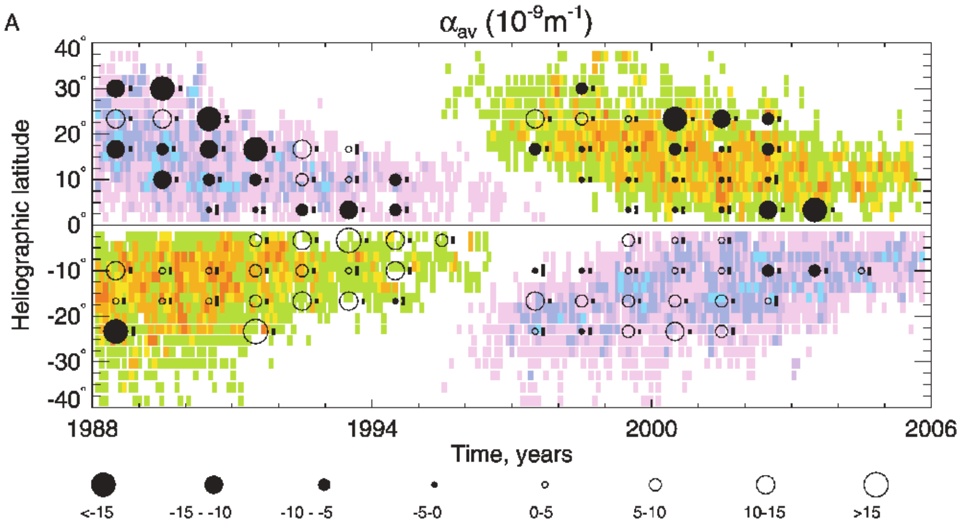


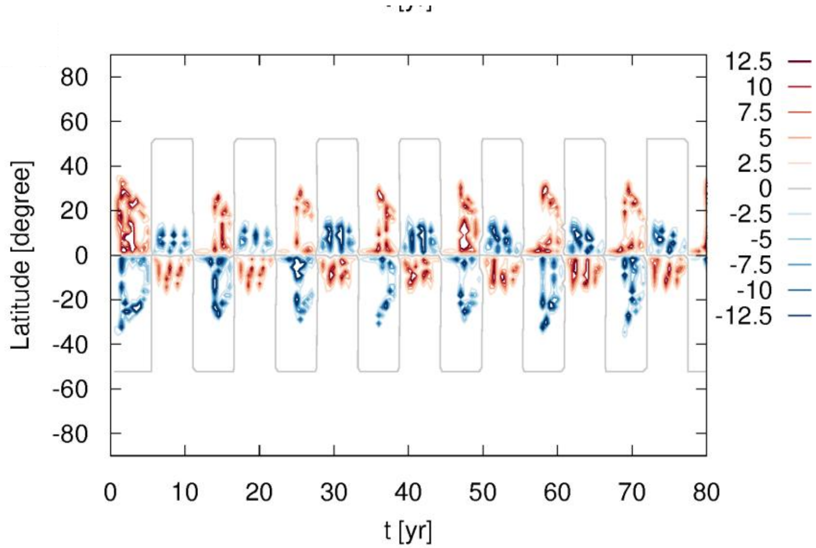


Stefani et al., arXiv:1803.08692

Some interesting features: Appearance of „wrong“ helicities

„Wrong“ helicites are frequently observed in the two hemispheres. They come out as an essential feature of the synchronization model…



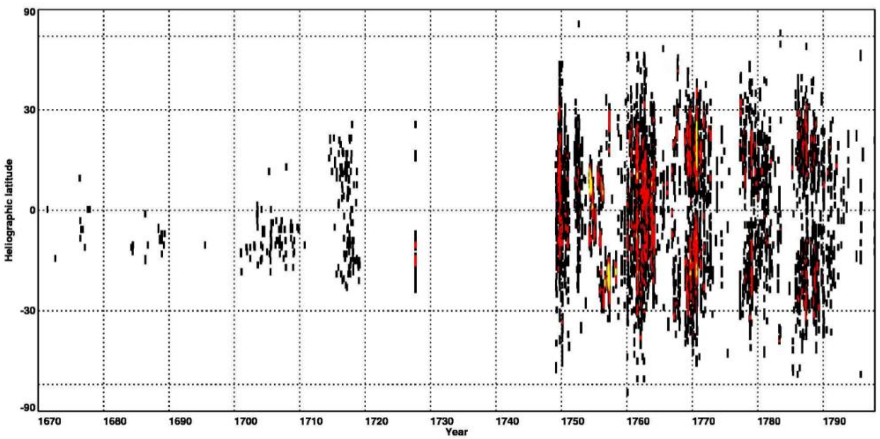


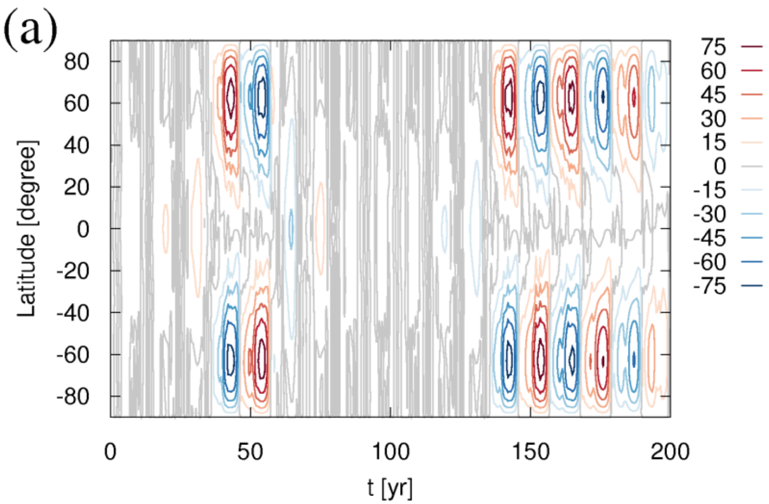
Zhang et al., MNRAS 402 (2010), L30

Stefani et al, arXiv:0803.08692

Some interesting features: Quadrupole fields around grand minima

During (or shortly after) grand minima, dipole fields may be replaced by quadrupole fields. These transitions appear in the synchronization model with maintained phase coherence.





Arlt and Weiss, Space Sci. Rev. 186 (2014), 525

Stefani et al, arXiv:0803.08692

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Any planetary synchronization model for the 60+++ years cycle?

Perhaps...

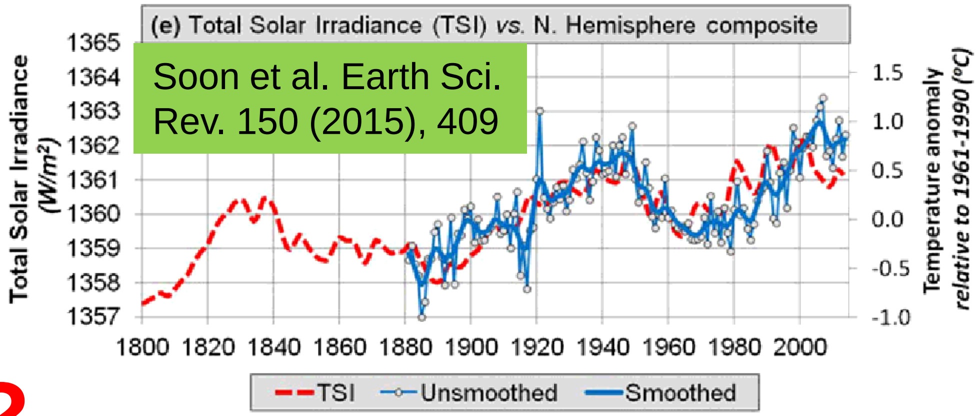
Mercury has nearly as strong a tidal forcing as Earth.

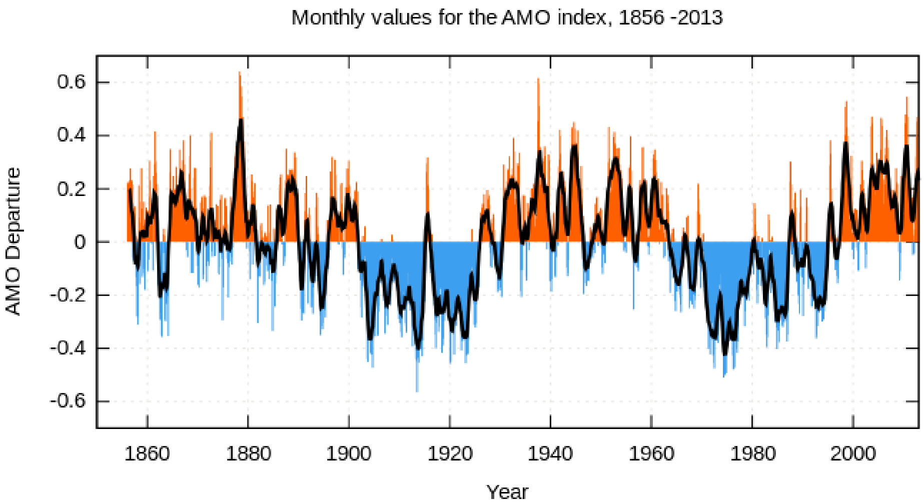
Period of Mercury, Venus, Earth, Jupiter alignments: **66.4 years**

Verma, S.D., 1986 Influence of planetary motion and radial alignment of planets on sun. In: Bhatnagar, K.B. Space dynamics and celestial mechanics, Astrophys. Space Sci. Libr. 127, Springer, 143

Soon, Connoly, Connoly, Earth-Science Review 150 (2015), 409

?





Atlantic Multidecadal Oscillation:
A simple sinus fit gives **66.3 years**

DRESDEN concept

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Summary and prospects

- Tiny tidal heights of 1 mm may translate (by naive virial theorem) to $v \sim (2\, g\, h)^{1/2} \sim 1$ m/s because of $g = 500$ m/s^2
- Babcock-Leighton models are rather stubborn to synchronization (but it‘s not excluded)
- Tayler instability at small Pm tends to produce intrinsic oscillations of the helicity and the corresponding α effect
- These helicity oscillations can be resonantly excited by m=2 perturbations (with minor energy input)
- Simple 0D and 1D $\alpha-\Omega$ dynamo models with an 11.07 years α oscillation produce a 22.14 years solar cycle
- High sensitivity of oscillations/pulsations on dynamo parameters (e.g. τ) → grand minima ?
- Higher dimensional models with realistic tachocline geometry and rotation are urgently needed!

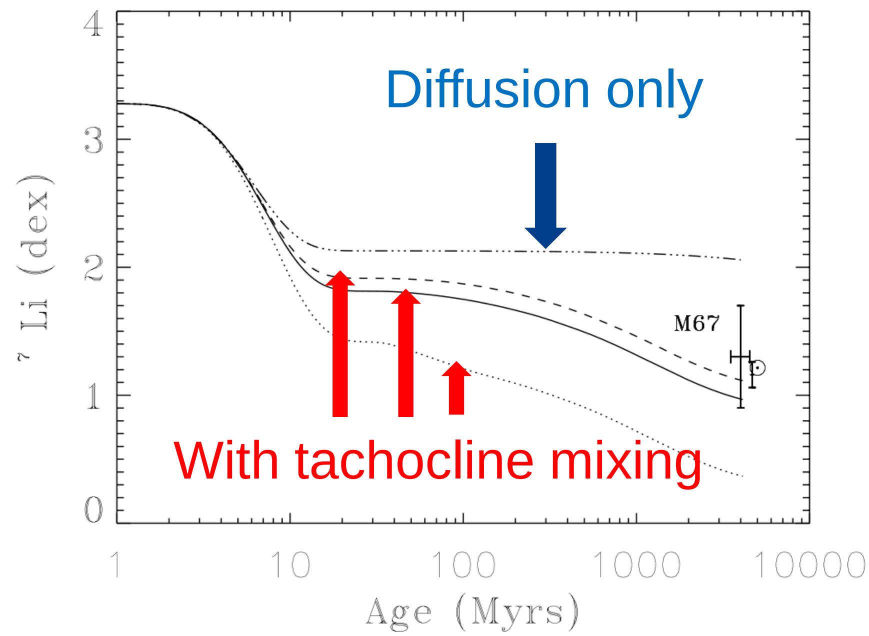
DRESDEN concept HZDR

Further prospects: Lithium depletion problem in the sun and stars

- Lithium and Beryllium are destroyed by proton captures at very high temperatures (Li 2.5×10^6 K, Be at even higher).

- These elements survive in outer (colder) convection zone of sun-like stars. Their observed continuous decrease suggests a transport process from the convection zone into the radiation zone, where they are destroyed.

- The transport mechanism needs to be rather slow (compared to turbulent convective motion).



^{7}Li surface abundances in stars with solar mass and composition. Tachocline mixing with disk coupling time 10, 3, and 0.5 Myr, respectively. 5777 K at 4.6 Gyr

Piau and Turck-Chieze, ApJ 566, 419 (2002)

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Lithium depletion problem in the sun and stars

- Mainly 2 candidates: convective overshooting, or a magnetic instability

- Problem: treating of mixing is not enough, the outward transport of angular momentum is essential.

- Turbulent Schmidt number (ratio of turbulent viscosity and mixing **Sc = ν*/D***. A value Sc≈100 is needed to explain the sun´s Li depletion

- Convective turbulence: strong mixing AND effective transport of angular momentum, thus a resulting Schmidt number Sc≈1.

- MHD instability: mild mixing and effective angular momentum transport, Sc≈100 easily reachable (Gellert et al. 2014).

- Explanation: angular momentum transport is due to Reynolds AND Maxwell stress, but mixing is ONLY a hydrodynamic process.
  With a magnetically dominated state, the problem can be solved.

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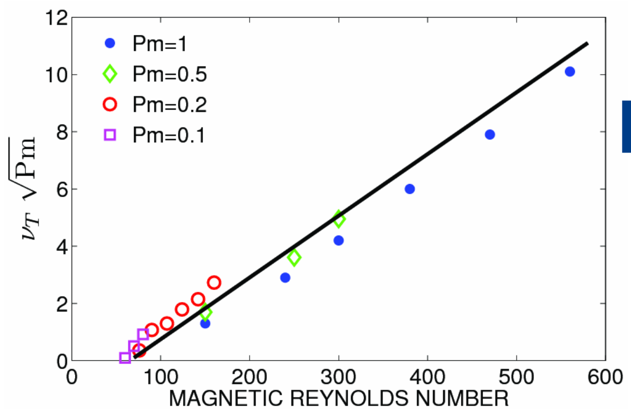
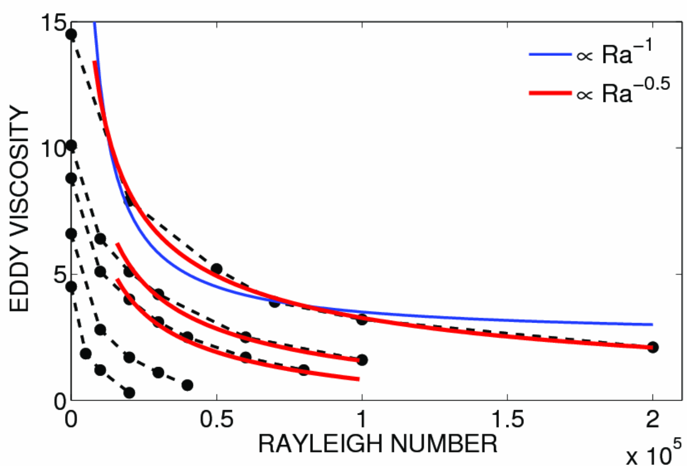
Astrophysical application of AMRI: Turbulent Schmidt number in stars

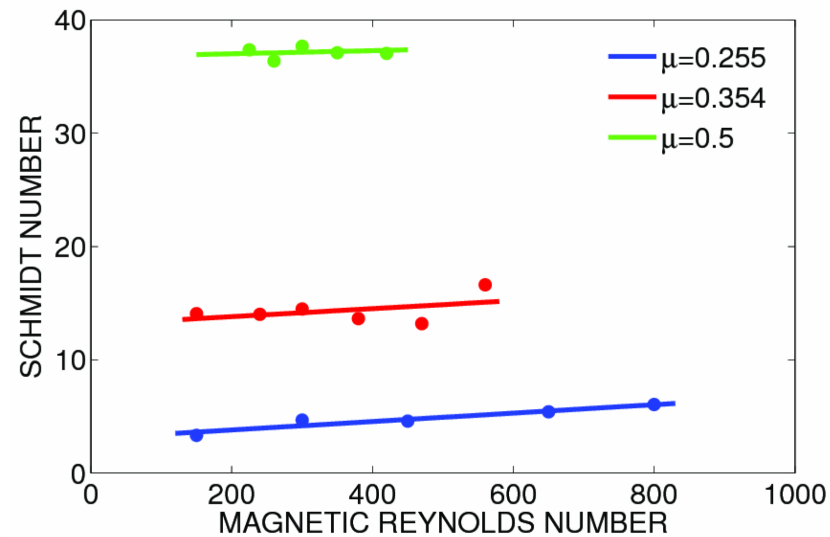
How to reconcile the slow-down of stars and the mild mixing of chemicals? Turbulent viscosity ν_T should be a few hundreds, the Schmidt number Sc= ν_T/D_T around 100.



Final scaling:

$$\frac{\nu_T}{\nu} \sim \sqrt{\frac{Pm}{Ra}\frac{\mathrm{Re}}{\mu_\Omega^2}}$$

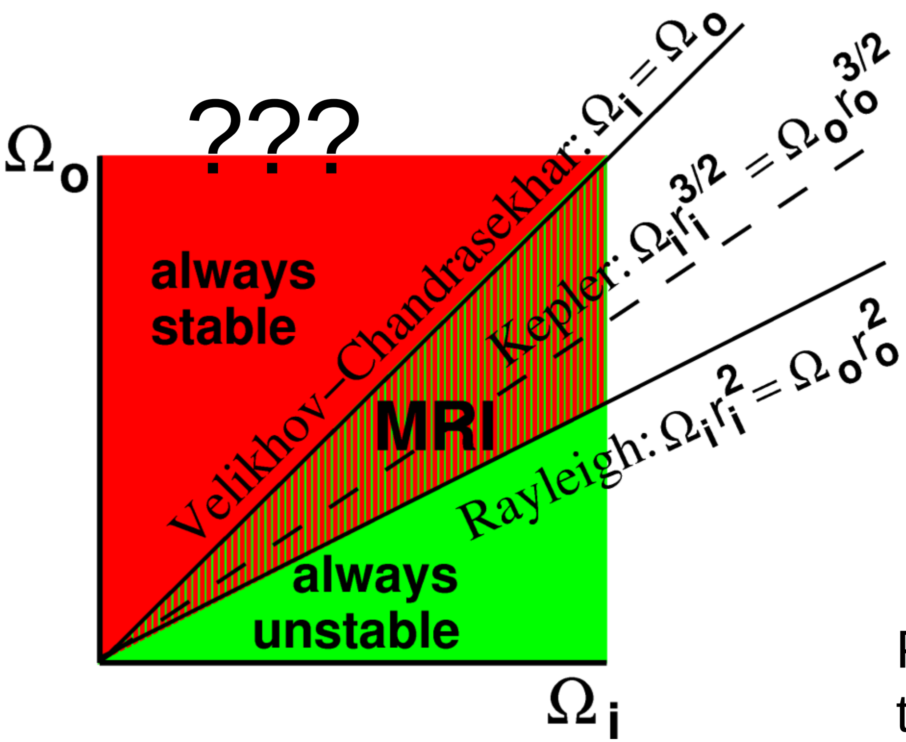


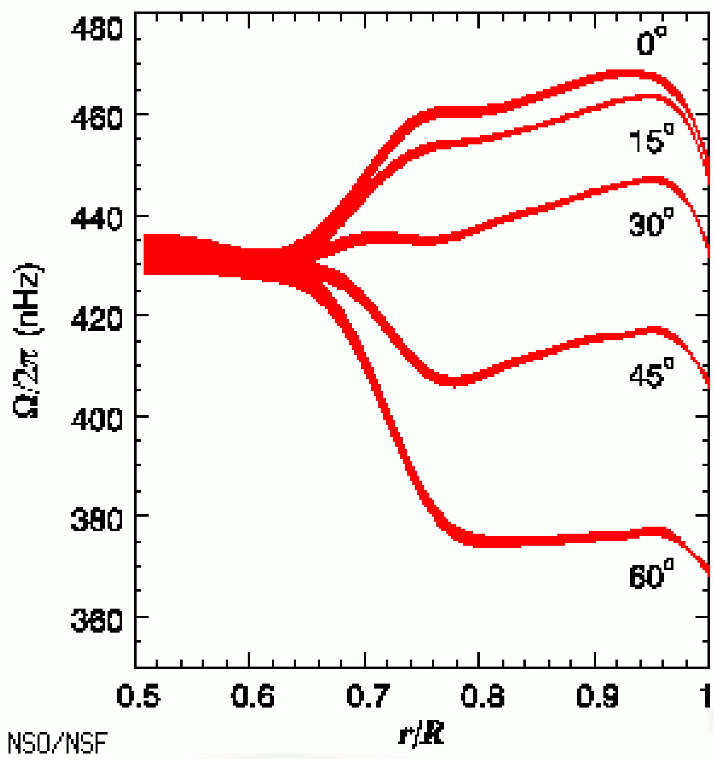


Gellert et al., IAUS 307 (2014)

Related questions: Any chance for a „Super-MRI“?

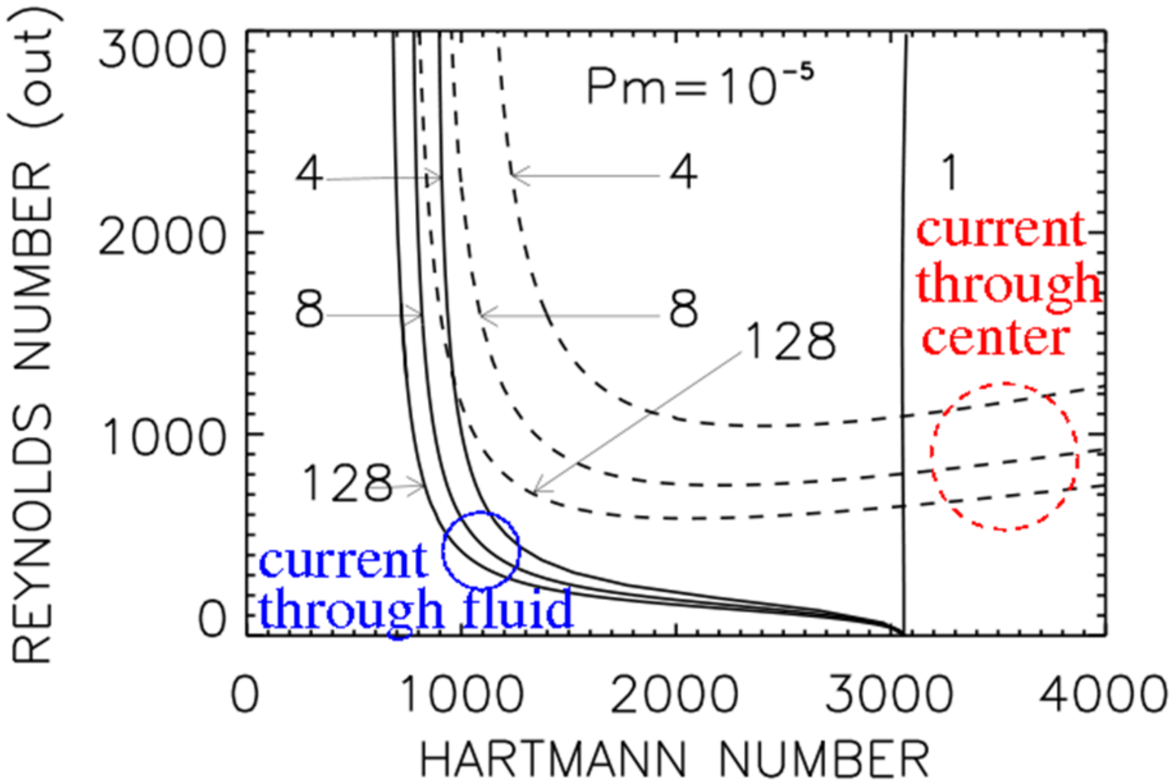
…i.e., can magnetic fields destabilize rotational flows with positive shear?





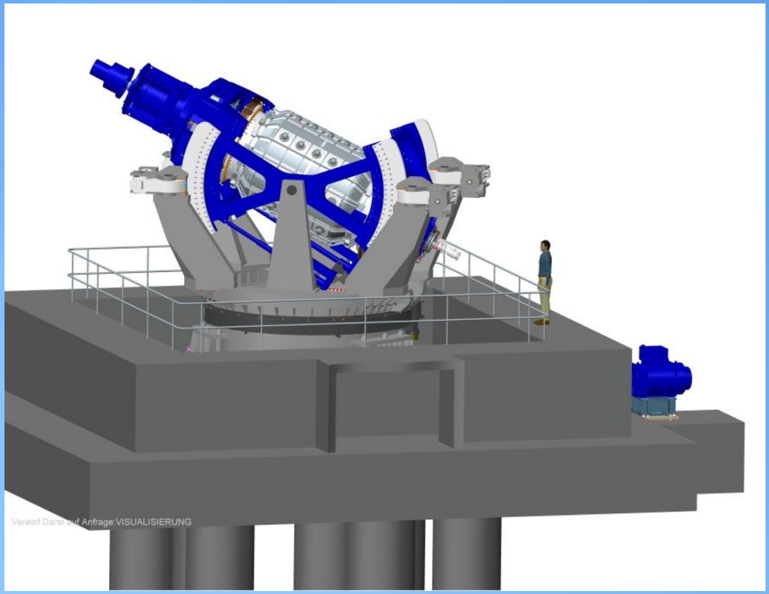
Possible relevance, e.g., for the solar tachocline in the equator-near strip…

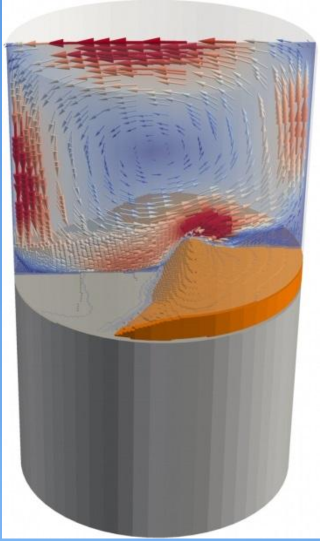
Evidence for „Super-AMRI“ in WKB and in 1D-stability code

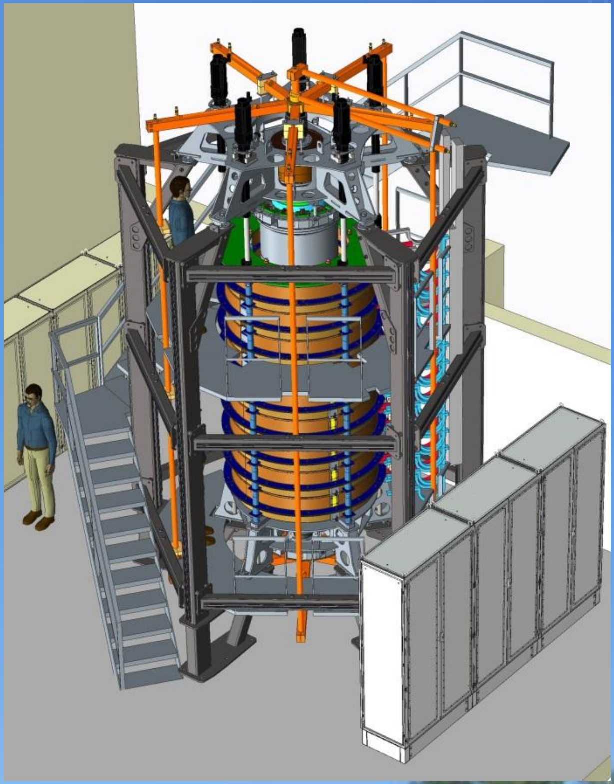


Stefani and Kirillov, Phys. Rev E 92 (2015) 051001(R)

Rüdiger et al, Phys. Fluids 28, 014105 (2016)







Thank you for your attention