„History of solar activity recorded in polar ice“
Dübendorf/Zürich, 14-15 November 2016

SYNCHRONIZED HELICITY OSCILLATIONS:

A LINK BETWEEN PLANETARY TIDES AND THE SOLAR CYCLE?

Frank Stefani, Vladimir Galindo,
André Giesecke, Norbert Weber, Tom Weier

HZDR
HELMHOLTZ
ZENTRUM DRESDEN
ROSSENDORF

Outline

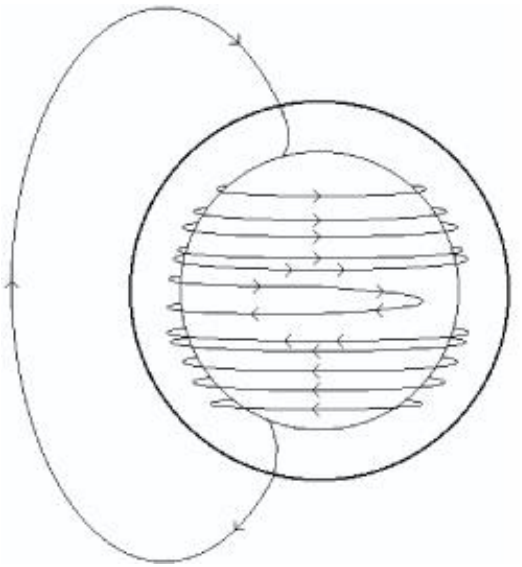
1. Solar dynamo models
2. Planetary motion and the solar dynamo
3. Tayler-Spruit dynamo and the helicity question
4. Resonant excitation of helicity oscillations
5. A simple model of a synchronized dynamo
6. Summary

Solar dynamo models
(the main road)

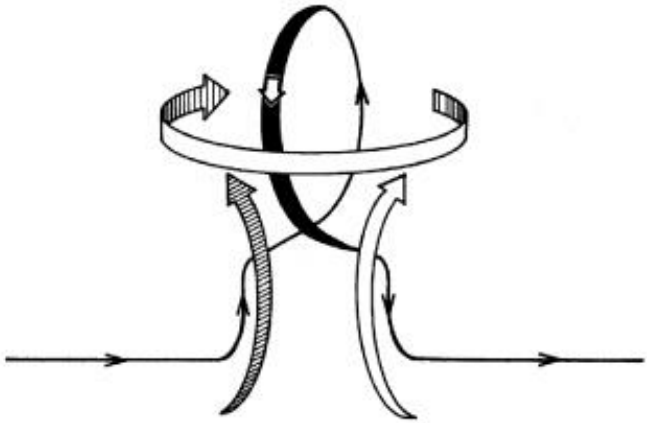
Solar dynamo models: Basics

Any solar dynamo needs:

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



Ω effect



α effect

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

Solar dynamo models: Basics

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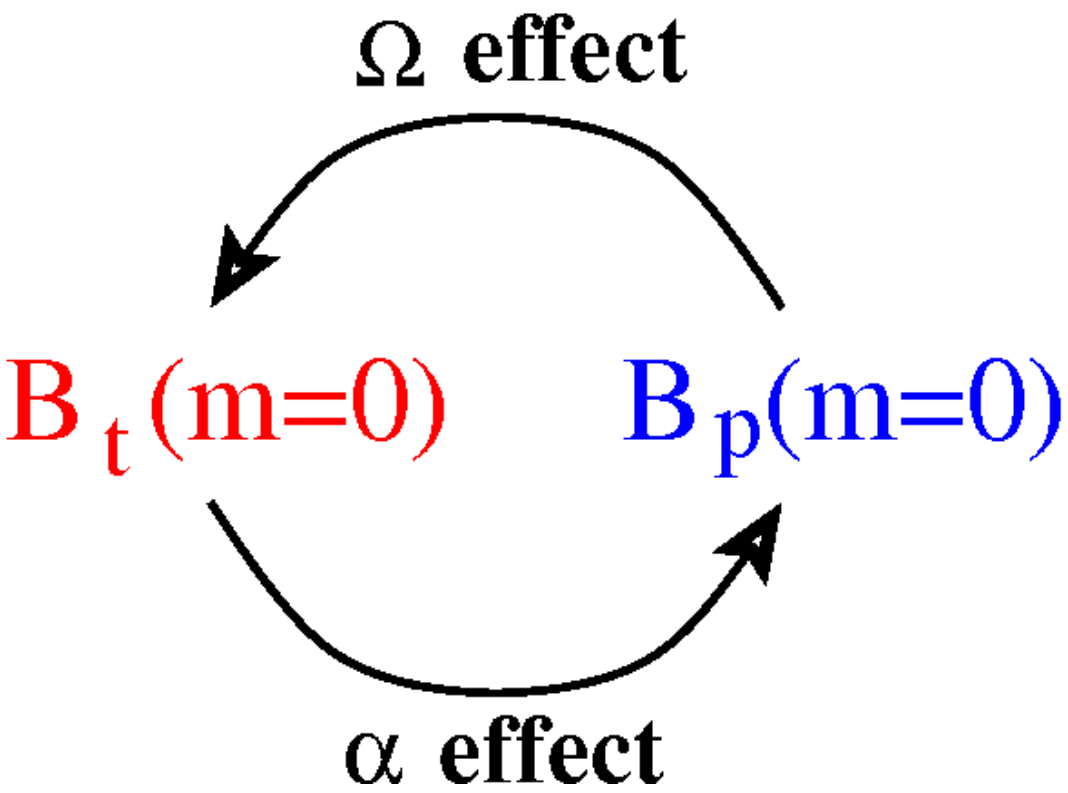
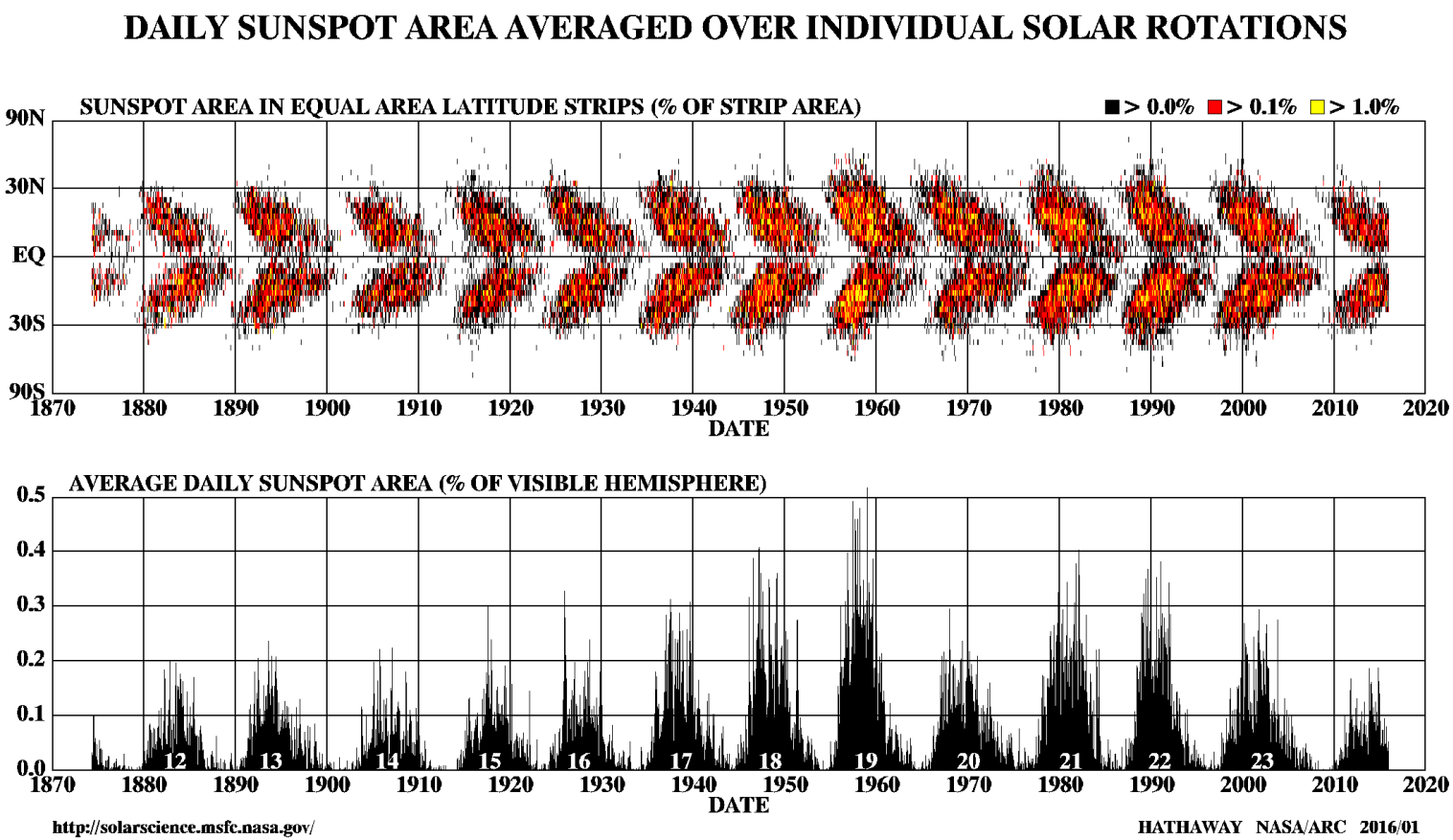


Solar dynamo models: Butterfly diagram of sunspots

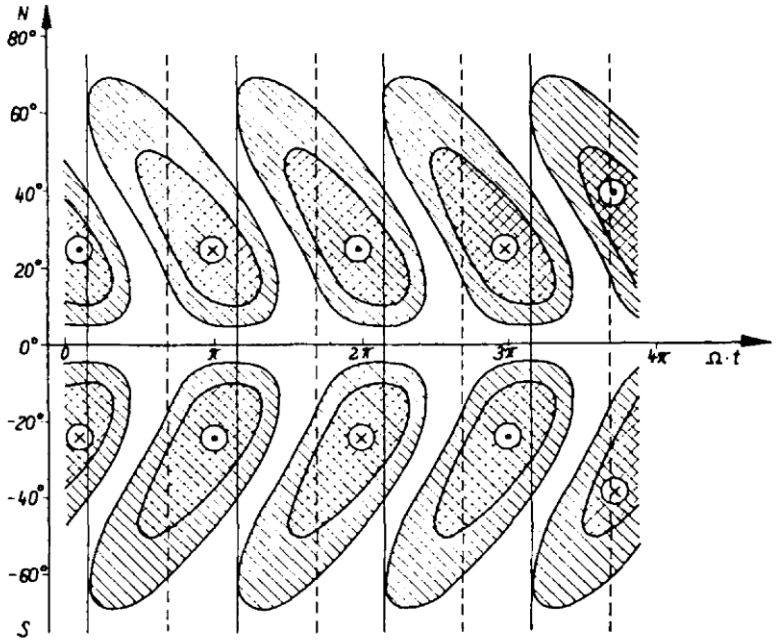
Parker-Yoshimura rule: product of α and $d\Omega/dr$ must be negative to provide the correct butterfly diagram of sunspots



Hathaway NASA/ARC 2016/01

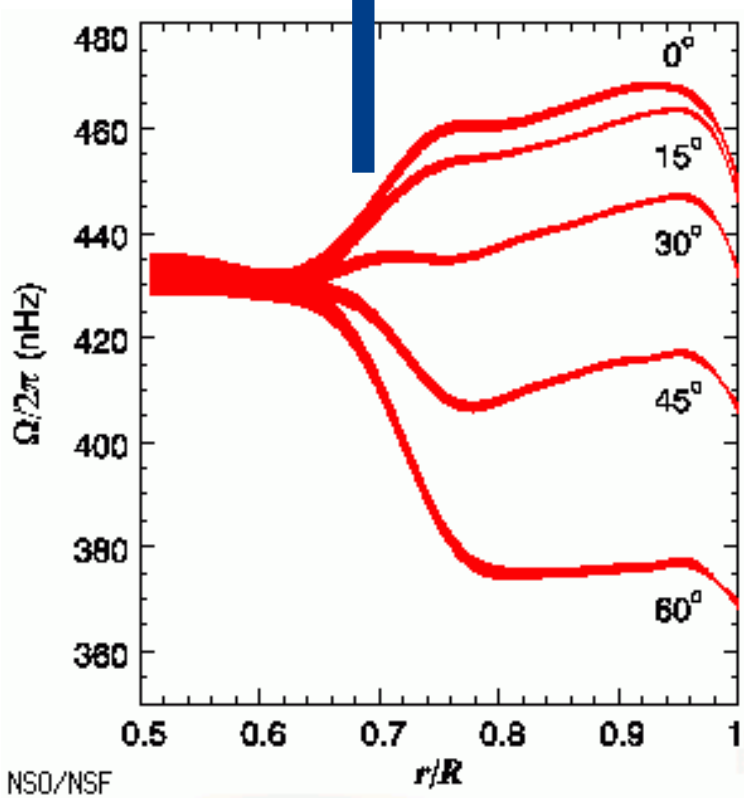
Solar dynamo models: Butterfly diagram of sunspots

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

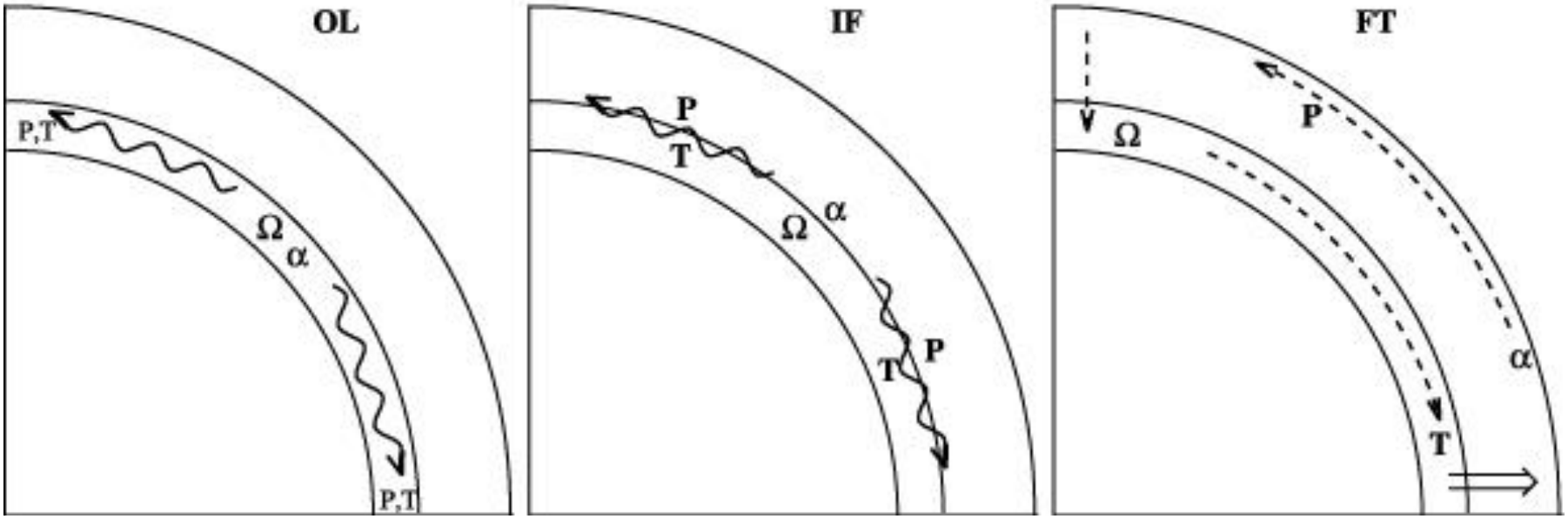


Steenbeck and Krause, Astron. Nachr. 291 (1969), 49

Later, helioseismology revealed positive $d\Omega/dr$ in the 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

Planetary motion and the solar dynamo (off the main road)

Planetary motion and the solar dynamo: an old idea of R. Wolf

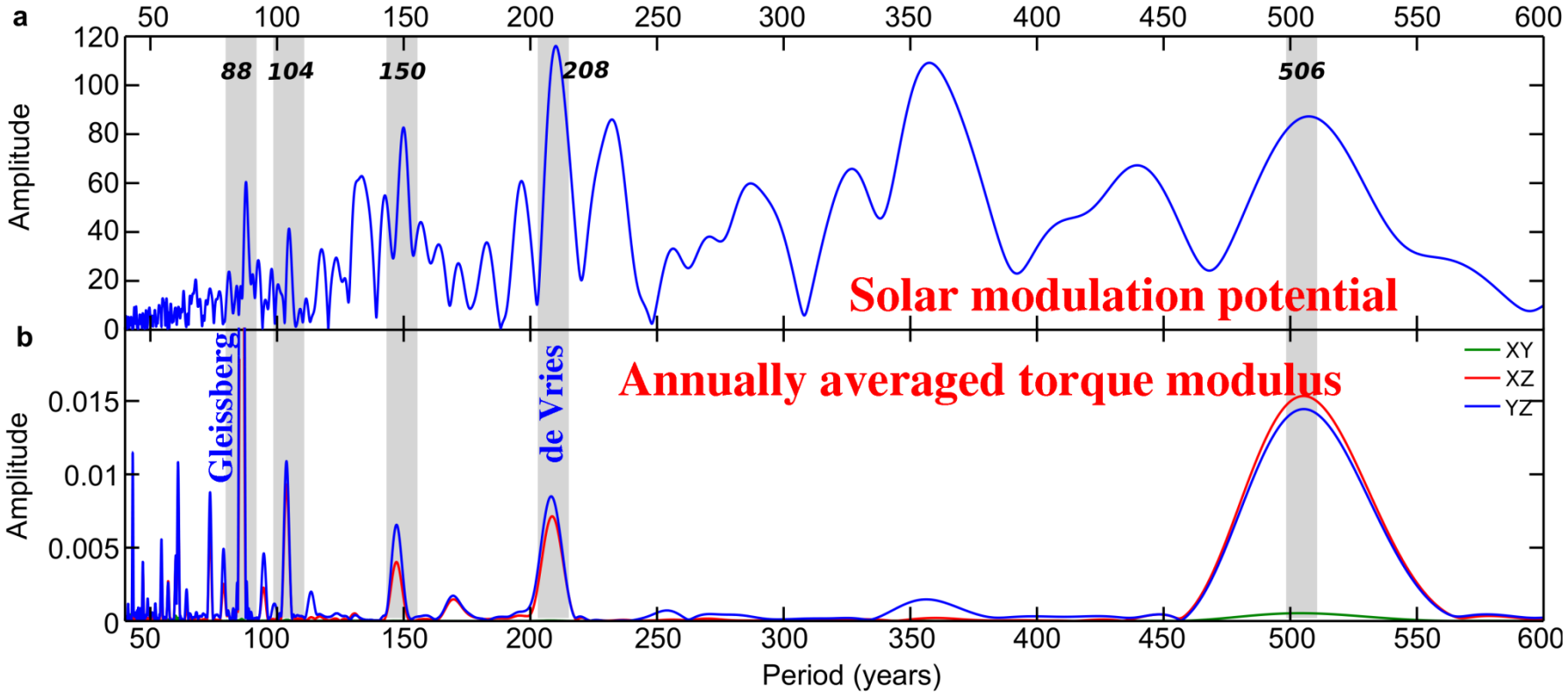
the researches commenced in the seventh number. I shall accordingly show, by employing, on the one hand, my own observations in the year 1849 to 1858; and on the other, extracts from the observations of Schwabe in the years 1826 to 1848, that the formula

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

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

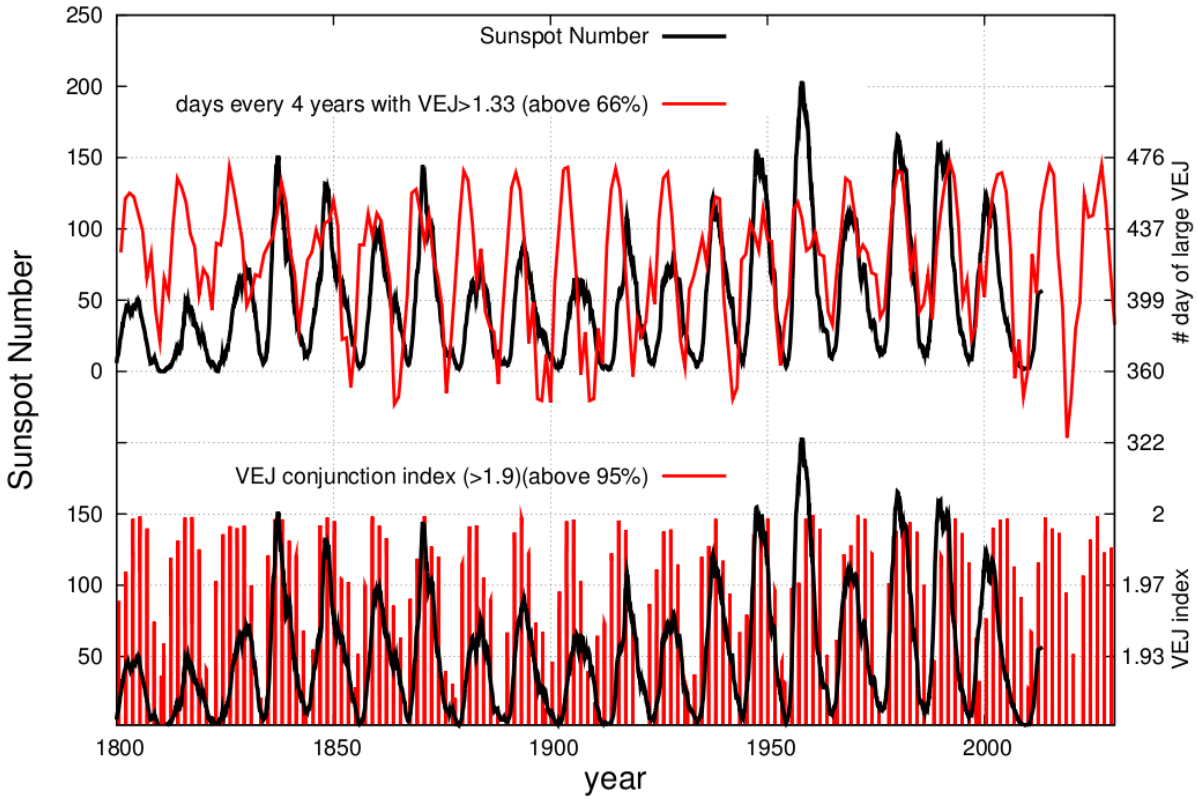
Planetary motion and the solar dynamo: recent results



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

Planetary motion 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!)



Accident, or something more…?

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; Scafetta, Pattern Recogn. Phys. 2 (2014), 1

Tayler-Spruit dynamo and the helicity question

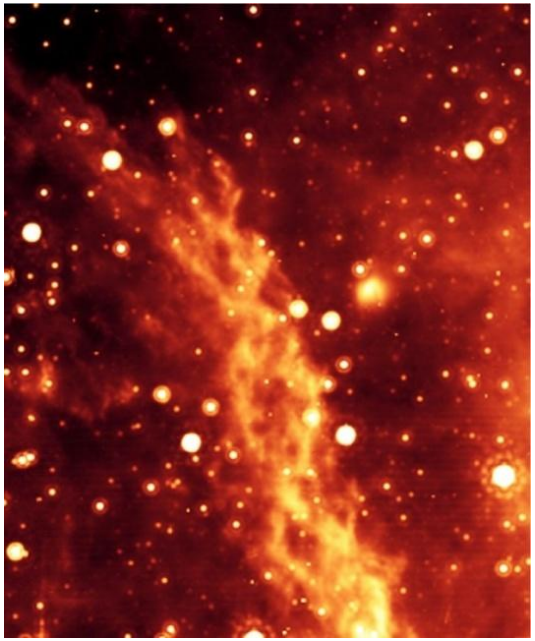
Tayler-Spruit dynamo: Kink-type Tayler instability (TI) at low Pm

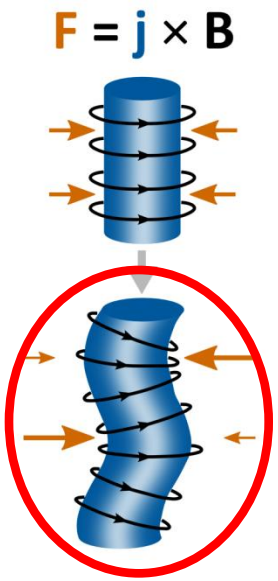
Astrophysical motivation:

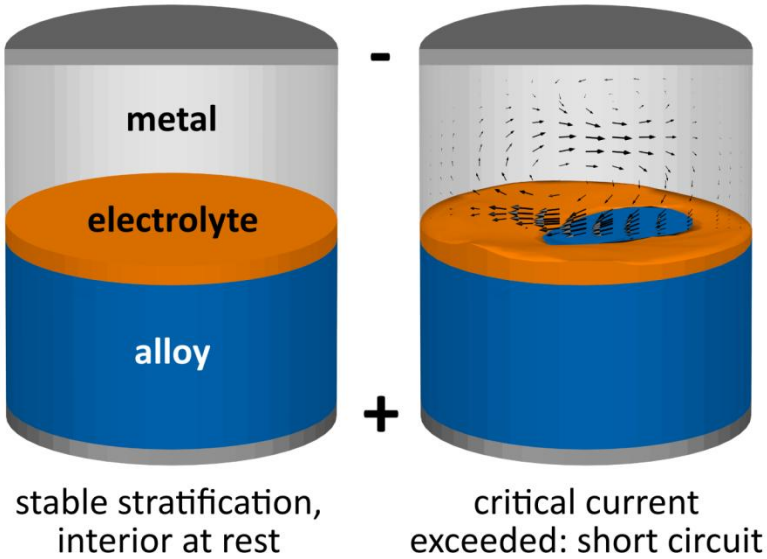
- Alternative mechanism of solar dynamo (Tayler-Spruit dynamo)
- Structure formation in cosmic jets

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: Integro-differential code for TI at low Pm

Initialisation: $\mathbf{J}_0, \mathbf{B}_0$

time step: CFL condition with Alfvén velocity

$$\mathbf{f}_\mathrm{L} = (\mathbf{J}_0 + \mathbf{j}) \times (\mathbf{B}_0 + \mathbf{b})$$

$$\rho \frac{D\mathbf{u}}{Dt} = -\nabla p + \eta \nabla^2 \mathbf{u} + \mathbf{f}_\mathrm{L}$$

$$\mathbf{b}(\mathbf{r}) = \frac{\mu_0}{4\pi} \int \frac{\mathbf{j}(\mathbf{r}') \times (\mathbf{r} - \mathbf{r}')}{|\mathbf{r} - \mathbf{r}'|^3} dV'$$

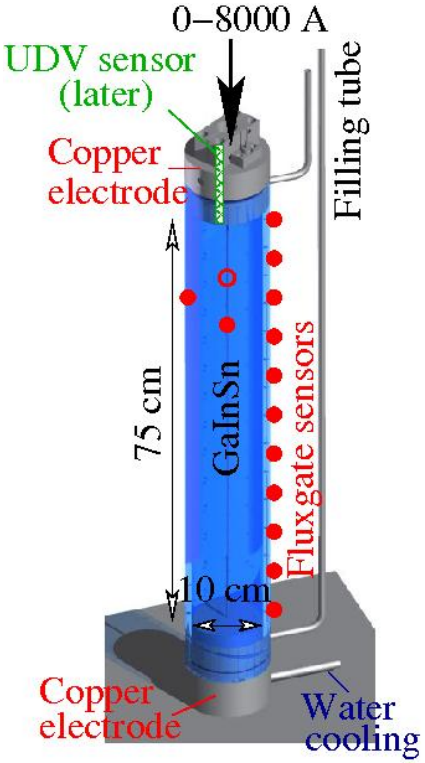
$$\mathbf{j} = \sigma(-\nabla\varphi + \mathbf{u} \times \mathbf{B})$$

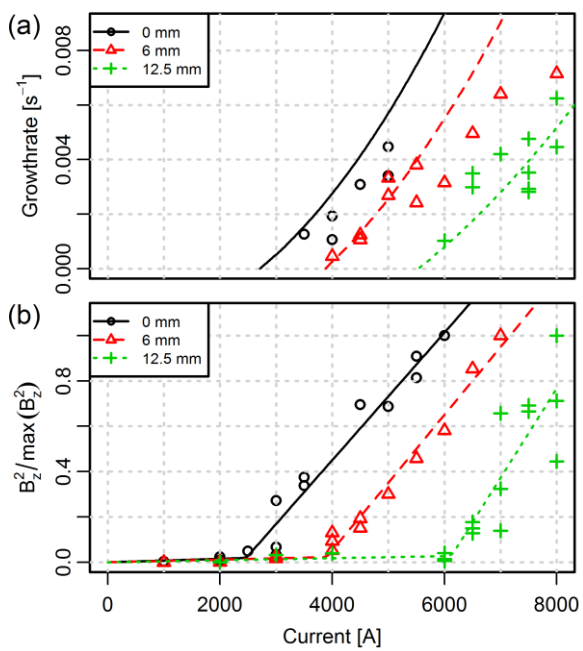
$$\Delta\varphi = \nabla \cdot (\mathbf{u} \times \mathbf{B})$$

Weber et al., New J. Phys. 15 (2013), 043034

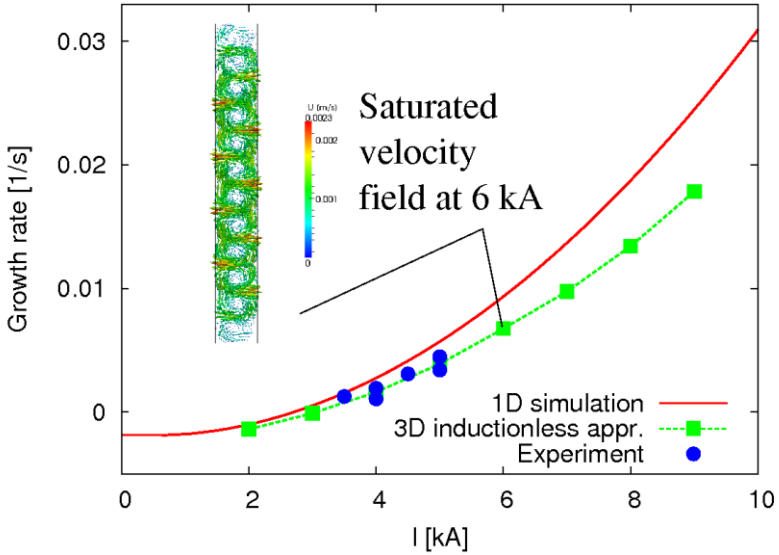
Tayler-Spruit dynamo: Experimental and numerical results for TI

Experiment





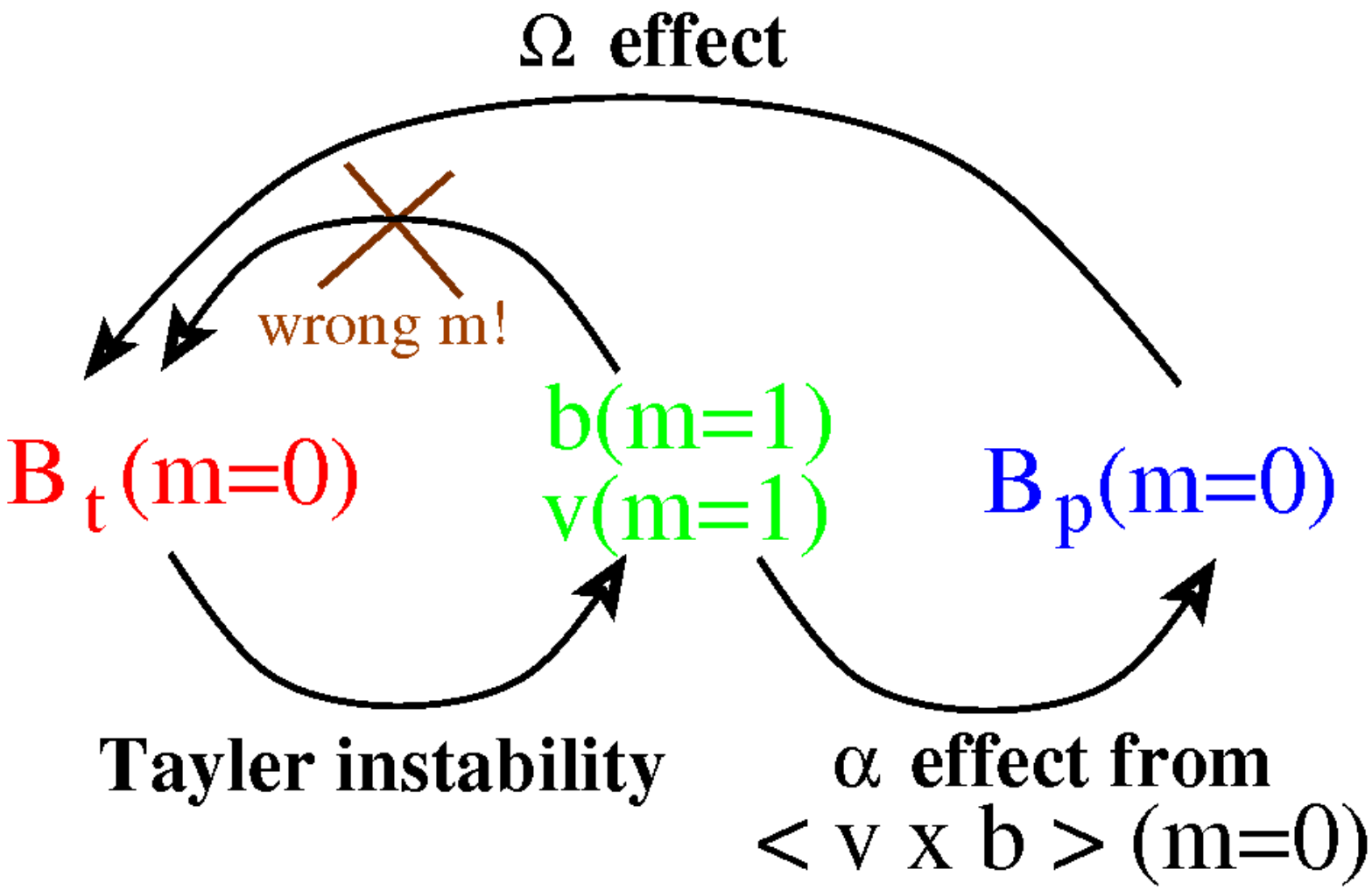
Numerics



Weber et al., New J. Phys. 15 (2013), 043034

Seilmayer et al., Phys. Rev. Lett. 108 (2012), 244501

Tayler-Spruit dynamo: the main problem



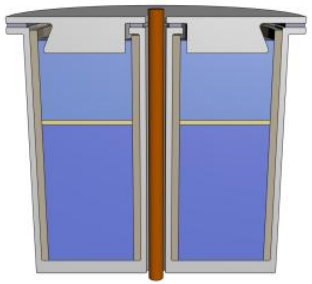
Spruit, Astron. Astrophys. 381 (2002) 923;

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

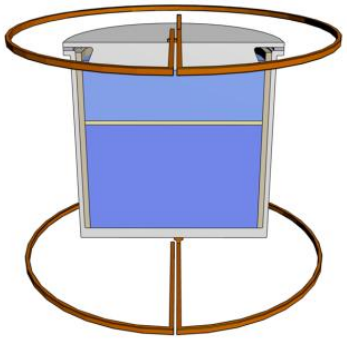
Tayler-Spruit dynamo: Saturation of TI and helical symmetry breaking

Ideal fluids, or Pm~1: Two mechanisms contribute to saturation (see also Taylor relaxation in reversed field pinches):

1. Radially dependent β effect → changes $B_\varphi(r)$ (acts like a return current)



2. α effect → produces B_z (stabilizes according to the Kruskal-Shafranov limit)



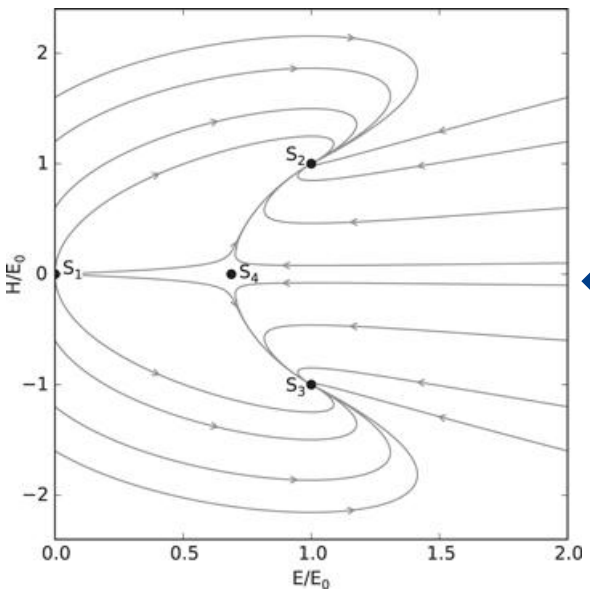
Stefani et al., Energy Conv. Managem. 52 (2011), 2982;

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

Tayler-Spruit dynamo: Saturation of TI and helical symmetry breaking

Simple Lagrangian leads to spontaneous symmetry breaking and mutual inhibition of the two helicities (like in biology)

Helicity H



Energy E

$$\frac{dE}{dt} = 2\gamma E - 2(\mu + \mu_*)E^2 - 2(\mu - \mu_*)H^2$$

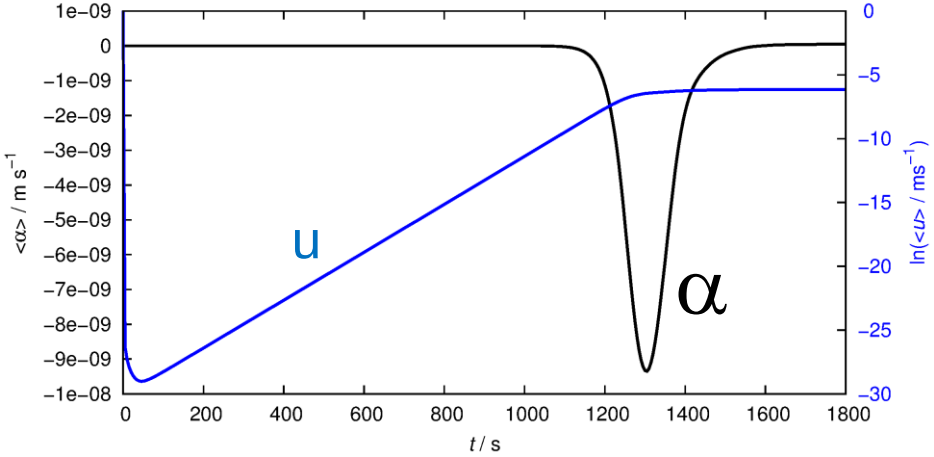
$$\frac{dH}{dt} = 2\gamma H - 4\mu E H$$

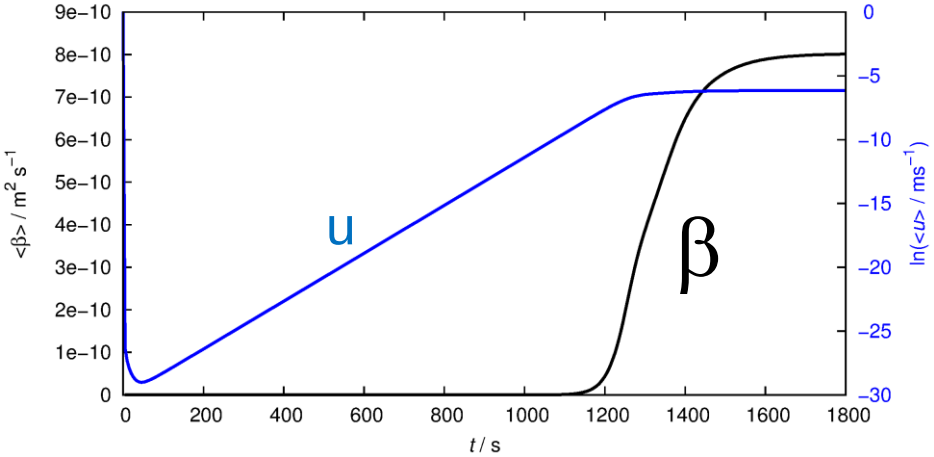
Bonanno et al., Phys. Rev. E 86 (2012); 016313;

Gellert et al., MNRAS 414 (2011), 2696

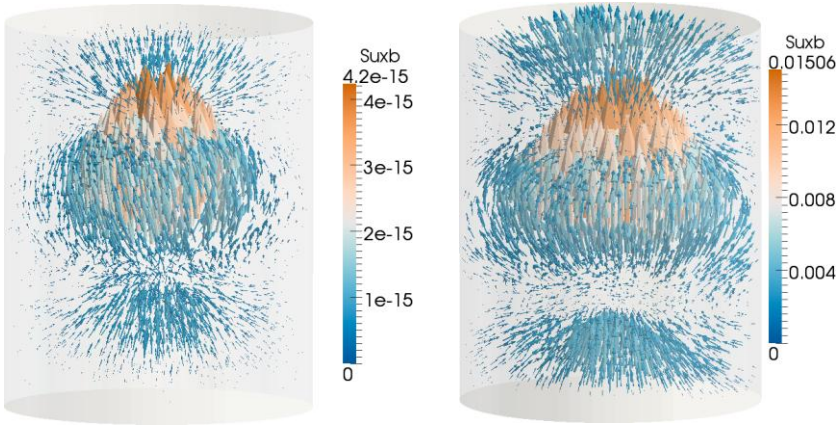
Tayler-Spruit dynamo: Helical symmetry breaking at low Pm

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…



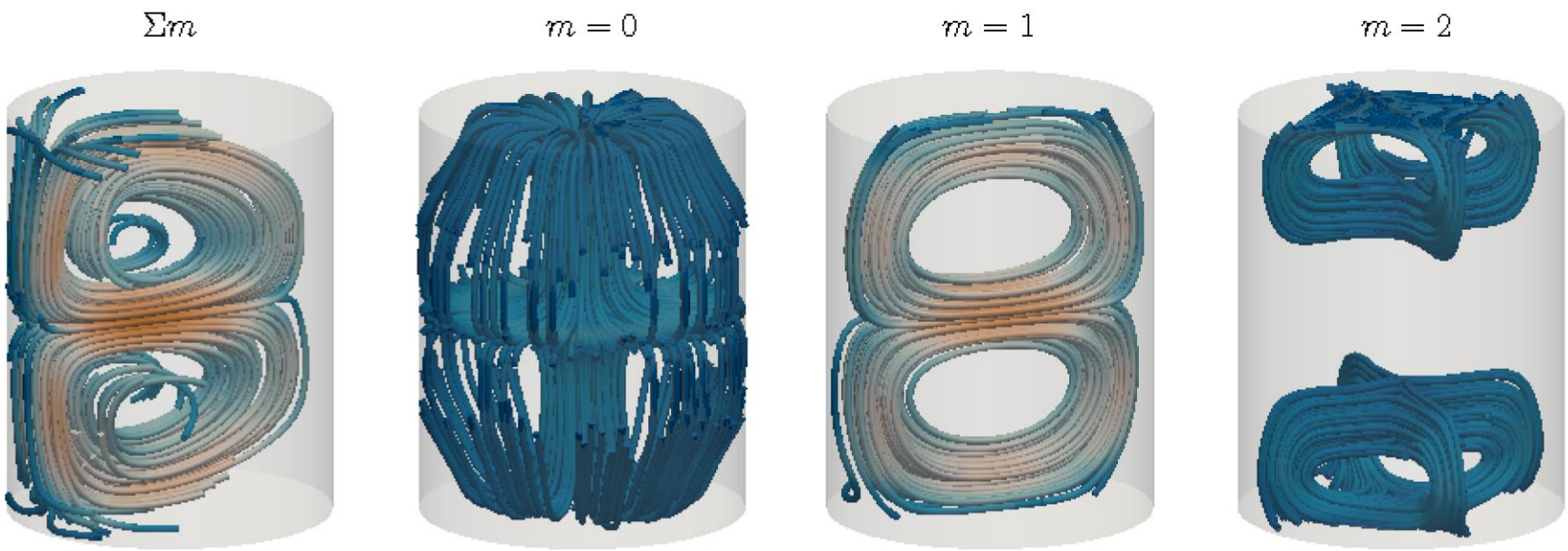
500 s 1800 s

Example: h/d=1.25, Ha=55

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

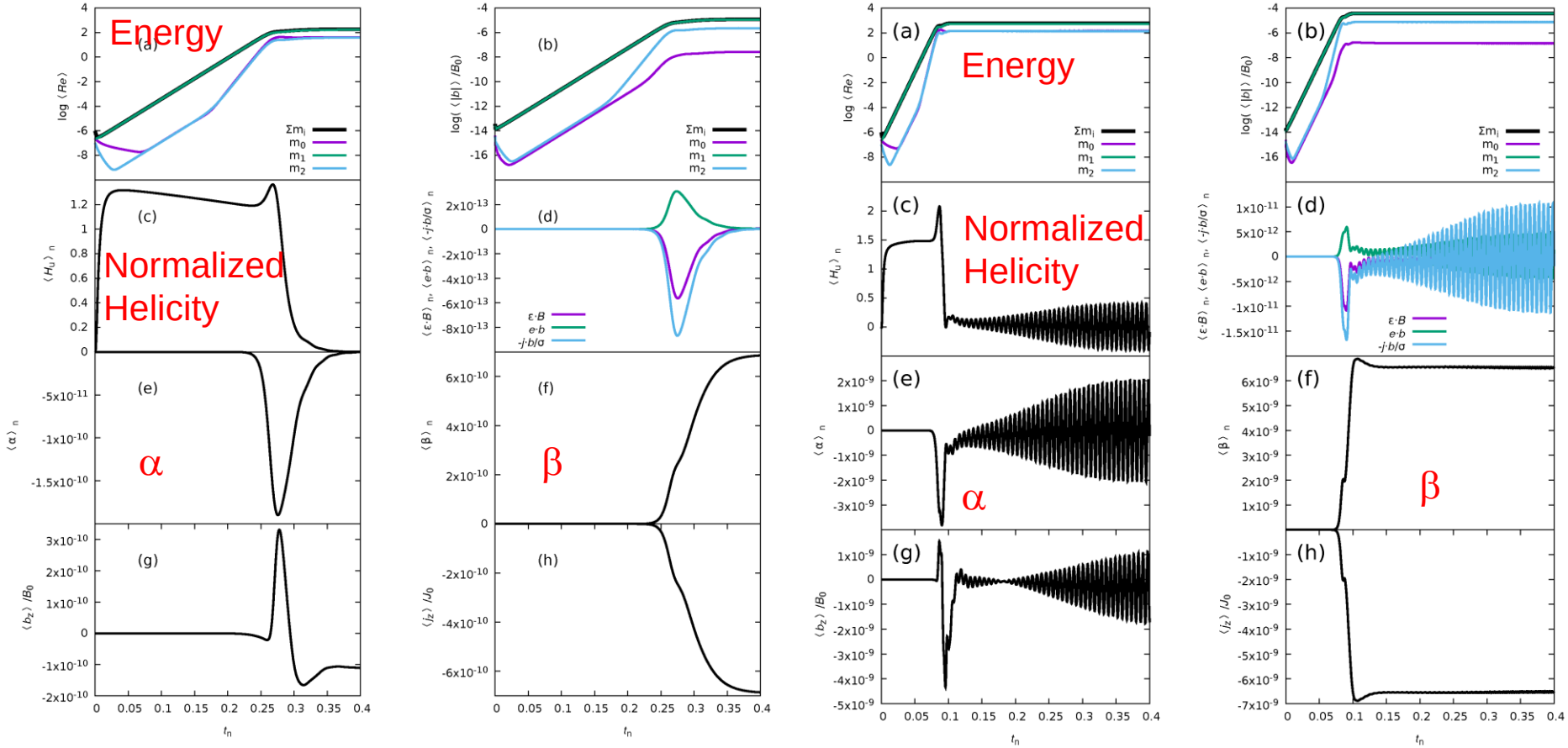
Tayler-Spruit dynamo: Saturation at low Pm

At low Pm, the saturation mechanism relies exclusively on the modification of the hydrodynamic base state (nonlinear appearance of m=0 and m=2 flow contributions).



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

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



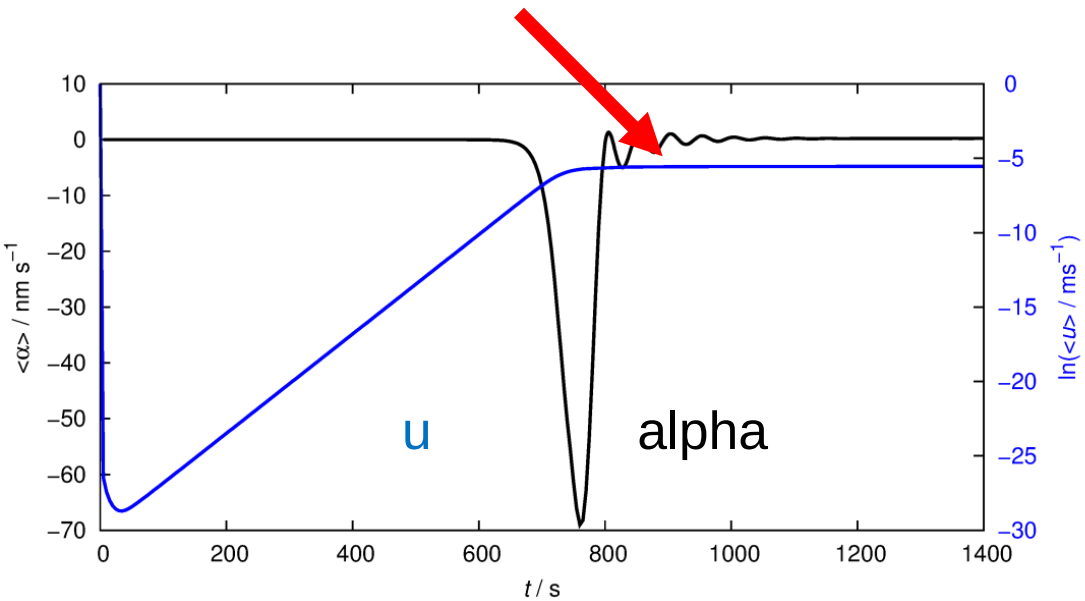
Ha=60

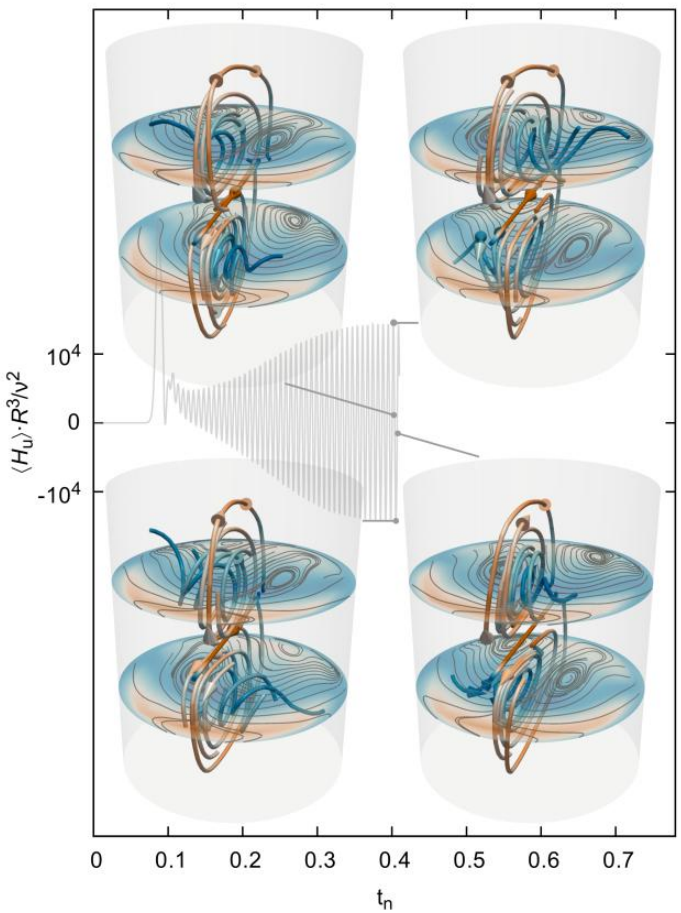
Ha=100

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

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

(Damped) helicity oscillations Ha =70

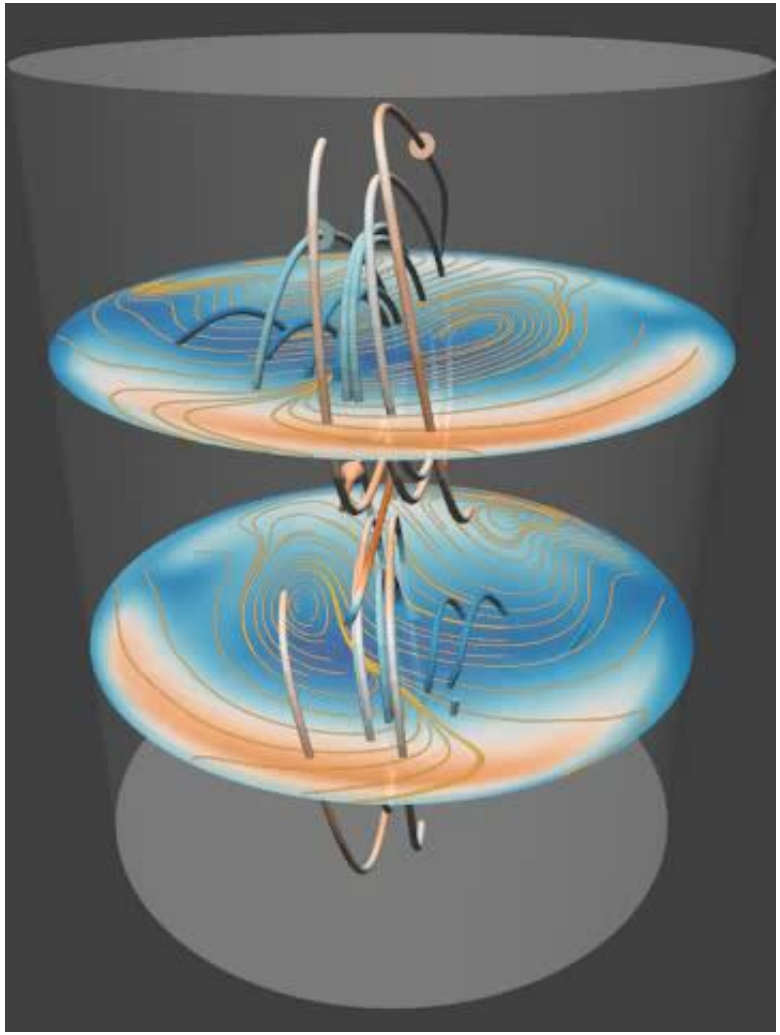




Ha =100

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

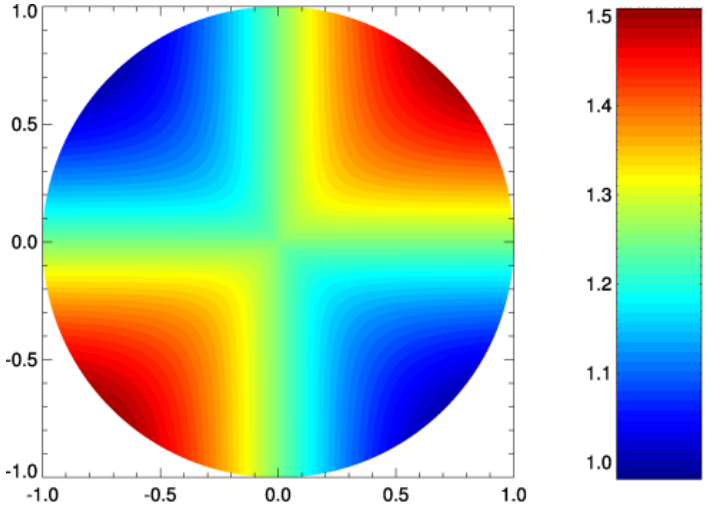
Resonant excitation of helicity oscillations

Resonant excitation of helicity oscillations

Tayler-Spruit-like dynamo:

- Ω-effect due to differential rotation
- α-effect relies on chiral symmetry breaking
- α-oscillation can be triggered and synchronized by planetary torques (emulated here by a m=2 viscosity oscillation) **with negligible energy input**

m=2 viscosity perturbation

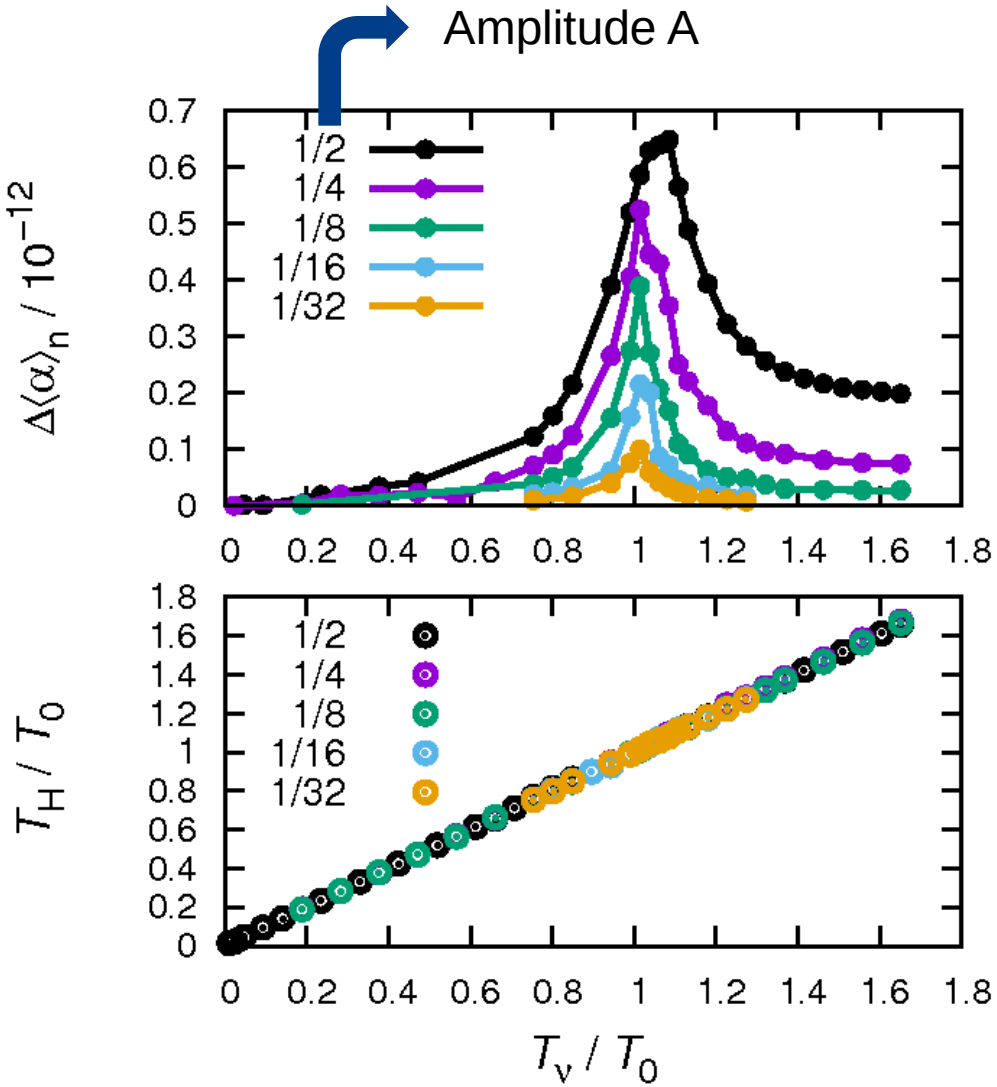


$$\nu(r,\phi,t) = \nu_0\{1 + A[1 + 0.5r^2/R^2 \sin(2\phi)(1+\cos(2\pi t/T_\nu))]\}$$

Amplitude A

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

Resonant excitation of helicity oscillations



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

Period of α oscillations shows 1:1 resonance.

A simple model of a synchronized dynamo

A simple model of a synchronized dynamo

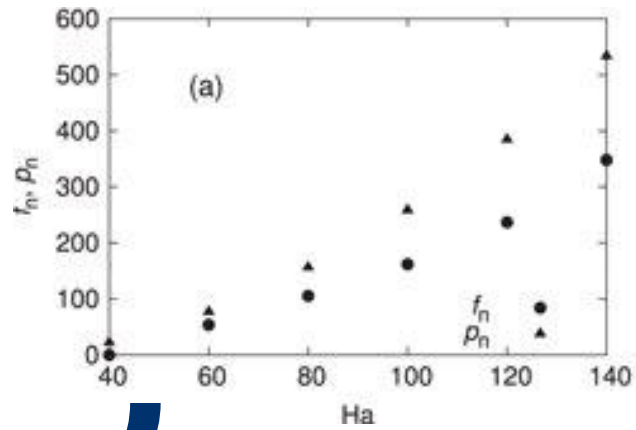
$$\dot{A}(t) = \alpha(t)B(t) - \tau^{-1}A(t)$$

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

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

Constant α term with quenching

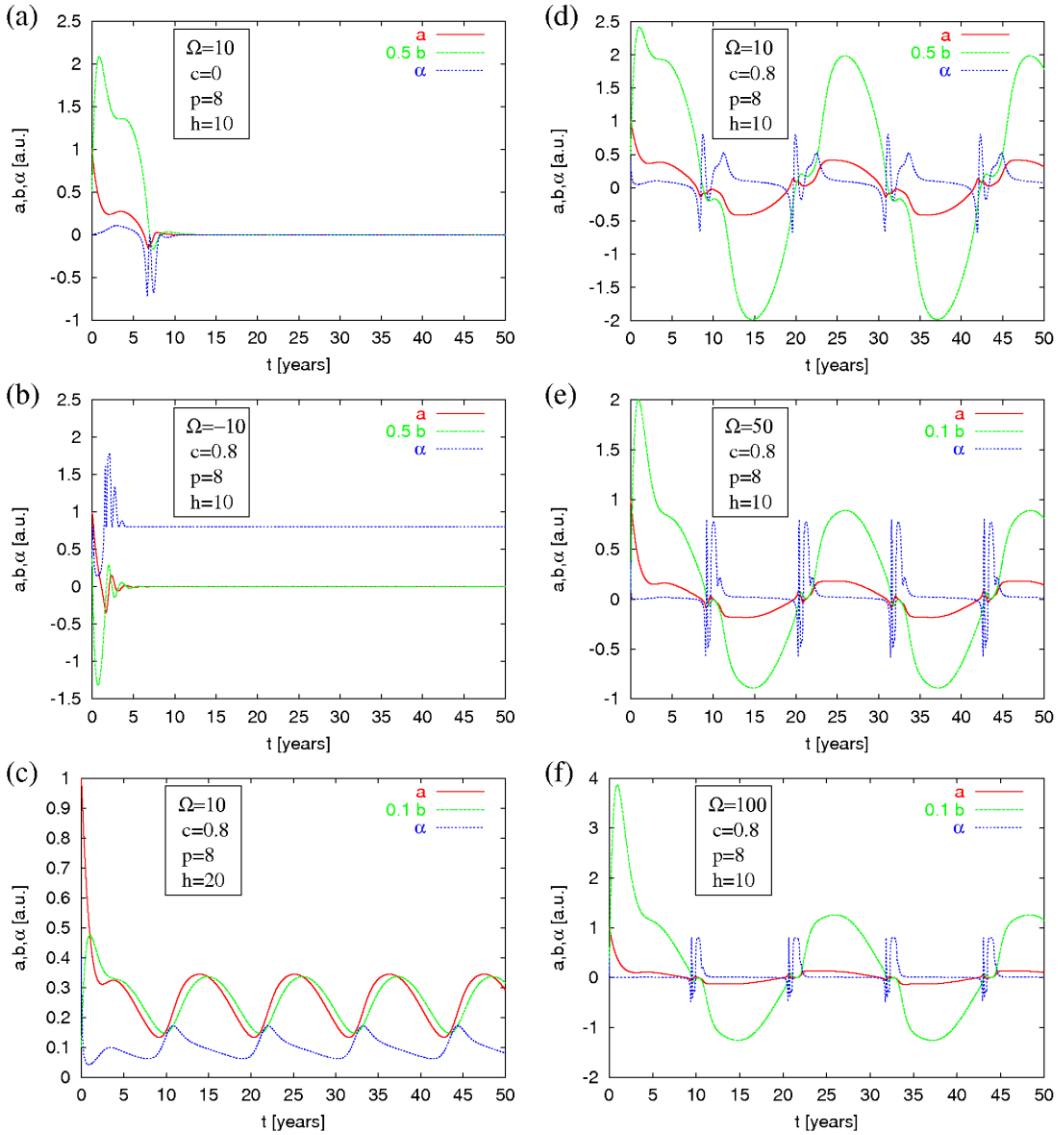
Oscillating α term with resonant dependence on the field strength (i.e., on the frequency of helicity oscillations)



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

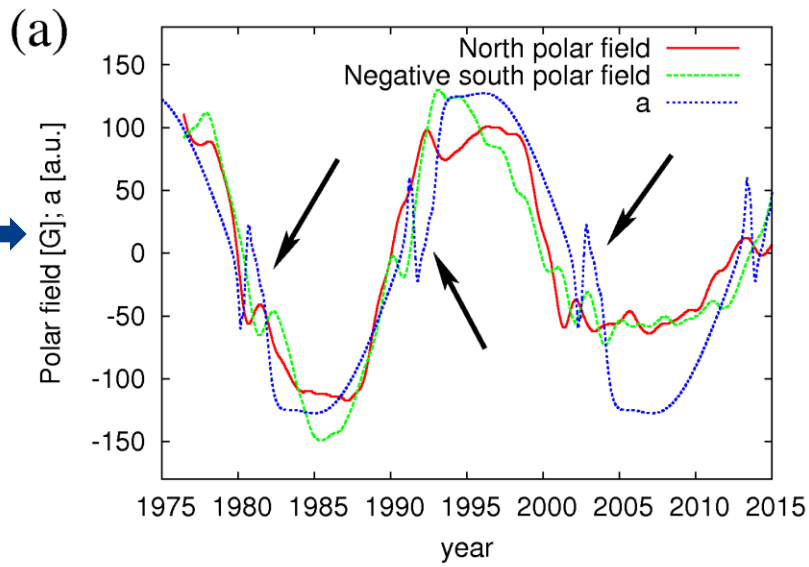
A simple model of a synchronized dynamo

For reasonable parameters, a robust 22.14 years Hale cycle appears…

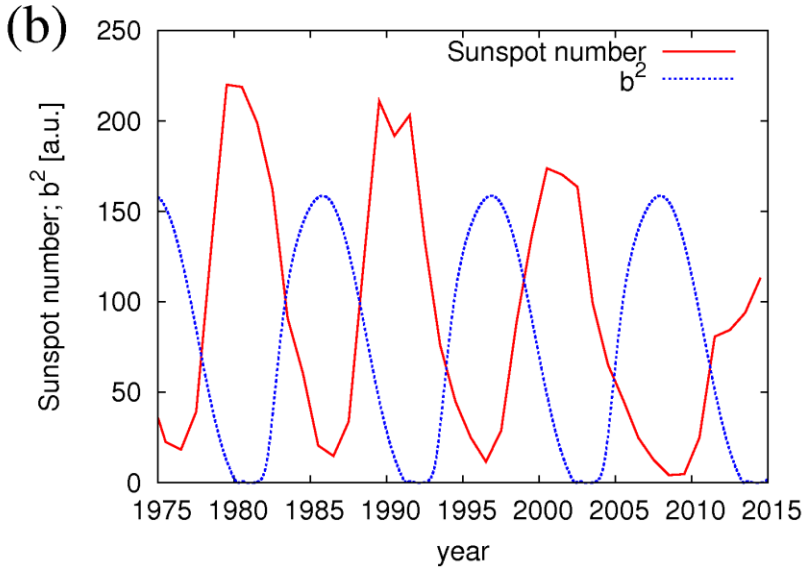


A simple model of a synchronized dynamo

μT



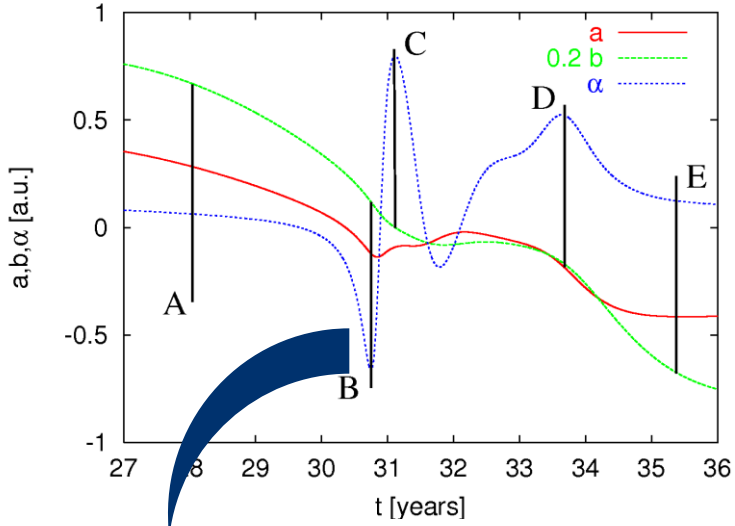
Comparison with measured polar field shows interesting „bumps“

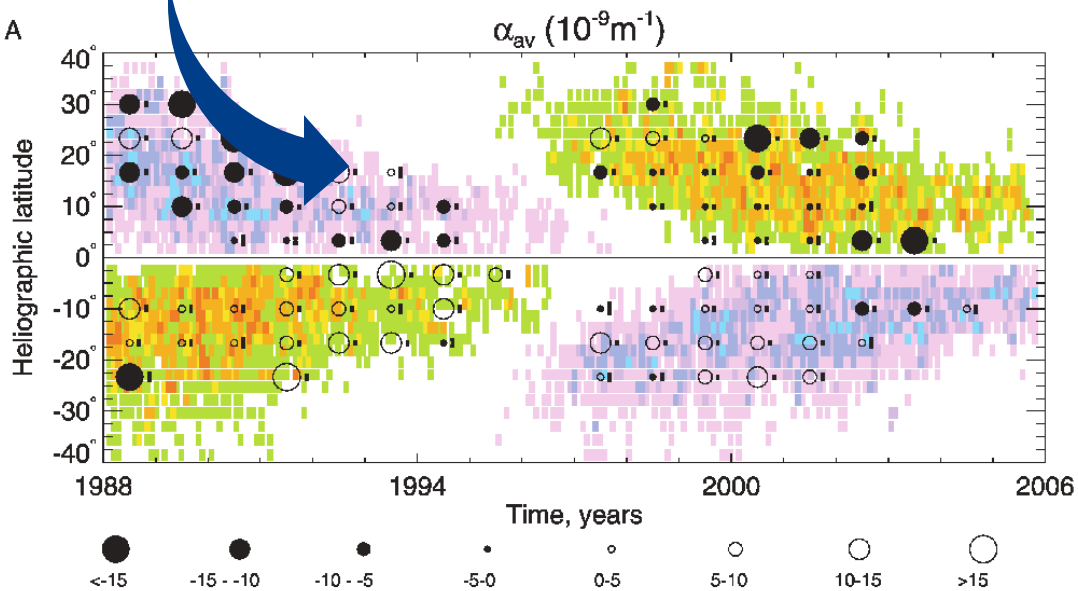


Usual problem of 0-dim models with missing phase shift between poloidal and toroidal field

Solution: rise time of flux tubes???

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

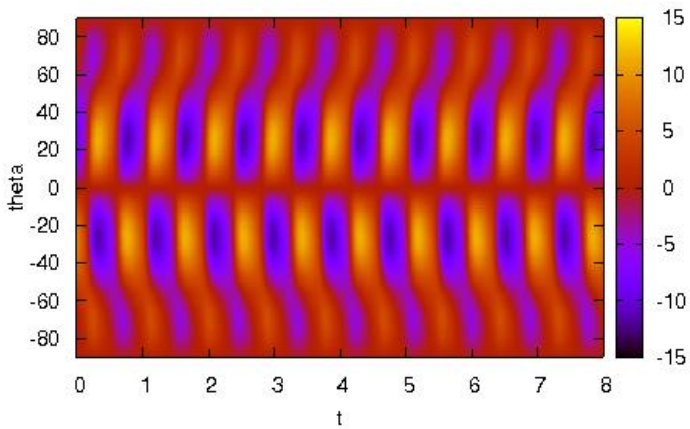
A simple model of a synchronized dynamo: slightly more complicated

$$a(\Theta,t) = a_1(t)\sin(\Theta) + a_2(t)\sin(3\Theta)$$

$$b(\Theta,t) = b_1(t)\sin(2\Theta) + b_2(t)\sin(4\Theta)$$

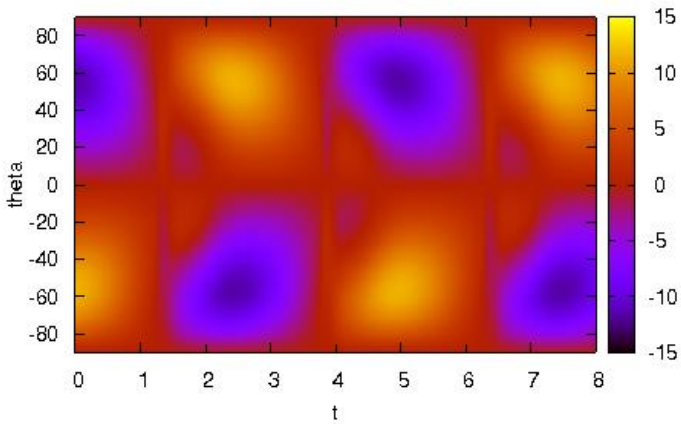
$$\alpha(t) = \frac{c}{1+gB^2(t)} + \frac{pB^2(t)}{1+hB^4(t)}\sin(2\pi t/T_V)$$

Nefedov and Sokoloff, Astron. Rep. 54 (2010) 247



c=+0.16, p=0, ω=+200

Wrong butterfly



c=+1.6, p=16, ω=+200

Correct butterfly

Stefani et al, arXiv:1610.02577

Summary

1. Tayler instability at small Pm tends to produce intrinsic oscillations of the helicity and the corresponding α effect
2. These helicity oscillations can be resonantly excited by m=2 perturbations (with small energy input)
3. A simple 0-dim α–Ω dynamo model with an 11.07 years α oscillation produces a 22.14 years solar cycle
4. Interesting coincidence of „bumps“ of the polar field, and of patches of „wrong“ helicity
5. Correct butterfly diagram for positive product of α and $d\Omega/dr$

Thanks for your attention…