Virtual Nordic Dynamo Seminar, 15th September 2020

Shaken and stirred: When Bond meets Suess-de Vries and Gnevyshev-Ohl

Frank Stefani

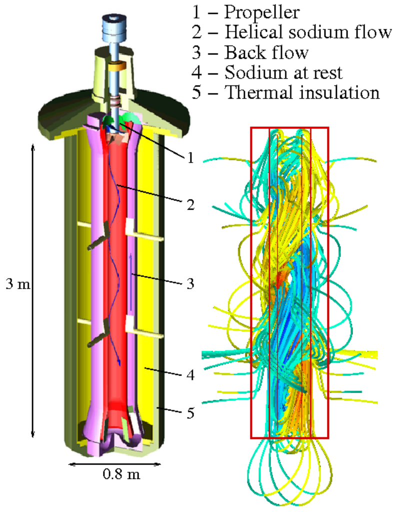
with thanks to
Jürg Beer (Zürich), André Giesecke, Rodion Stepanov (Perm),
Norbert Weber, Tom Weier

Solar Physics (submitted);
arxiv.org/abs/2006.08320

HZDR
HELMHOLTZ
ZENTRUM DRESDEN
ROSSENDORF

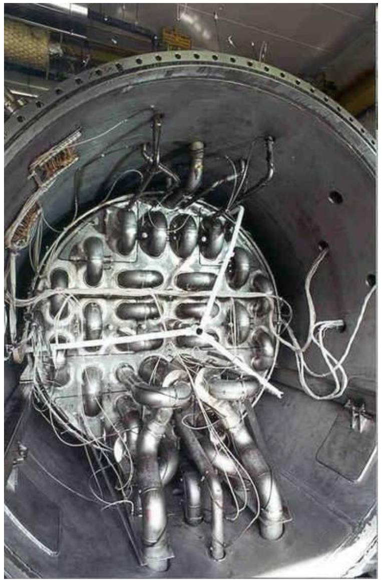
Things I won´t speak about

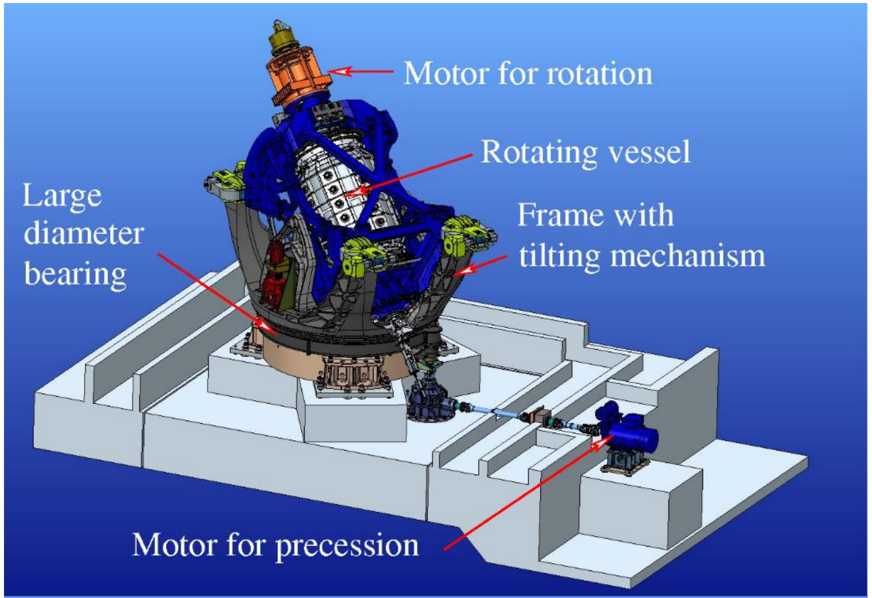
Liquid metal experiments on dynamo action and MRI

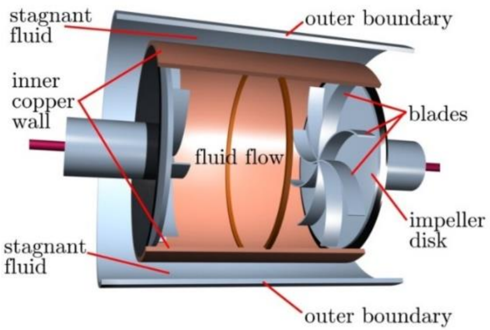


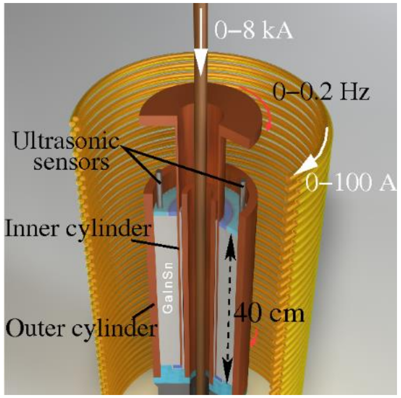
Dynamo module

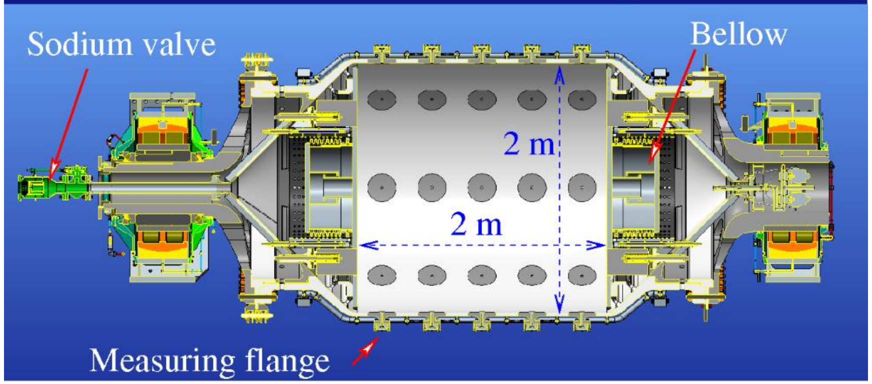
Simulated eigenfield





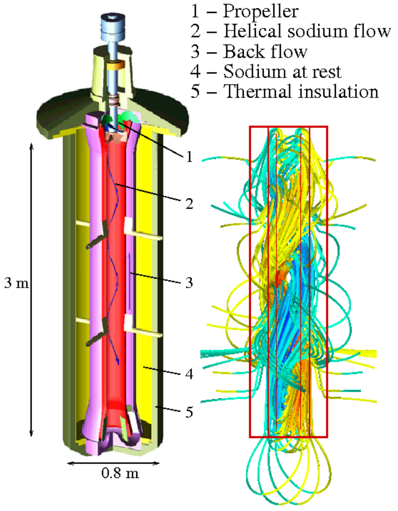






Gailitis et al., Rev. Mod. Phys. 74 (2002) 973; J. Plasma Phys. 84, 735840301 (2018); Stefani et al., Geophys. Astrophys. Fluid Dyn. 113 (2019), 51

Liquid metal experiments on dynamo action and MRI



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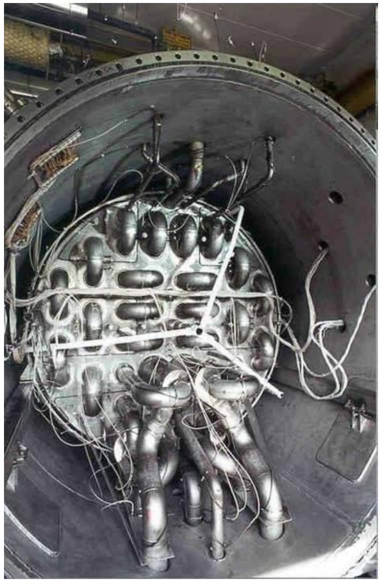
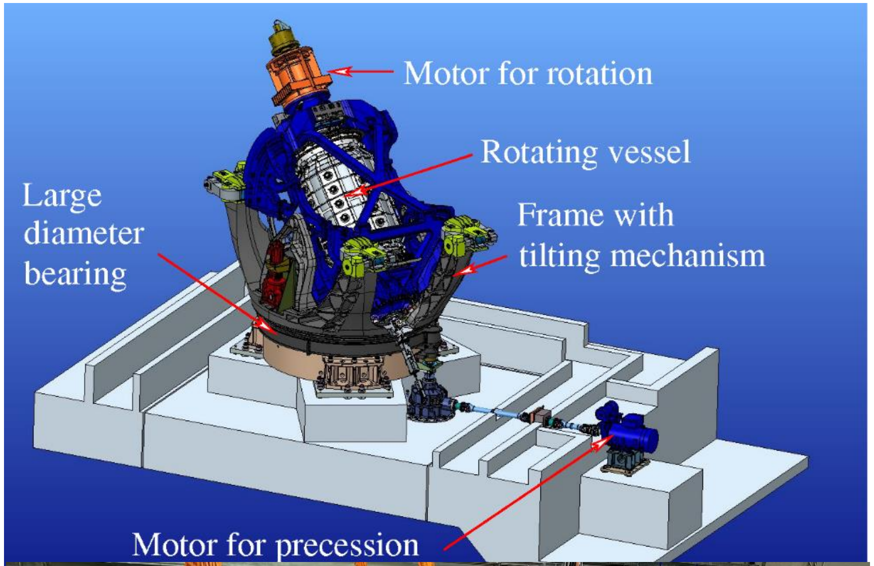
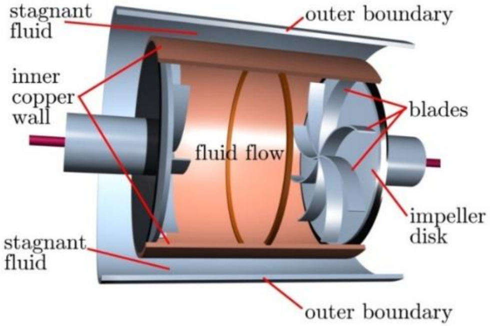
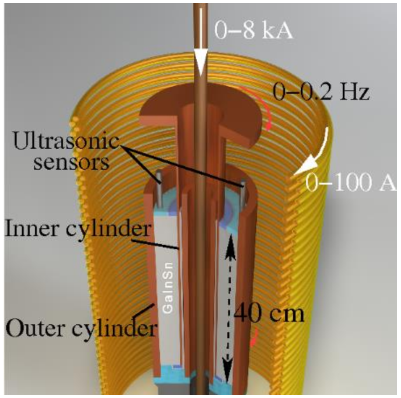
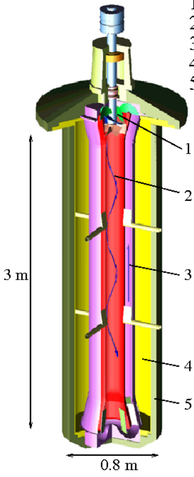






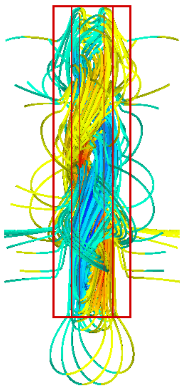


Liquid metal experiments on dynamo action and MRI

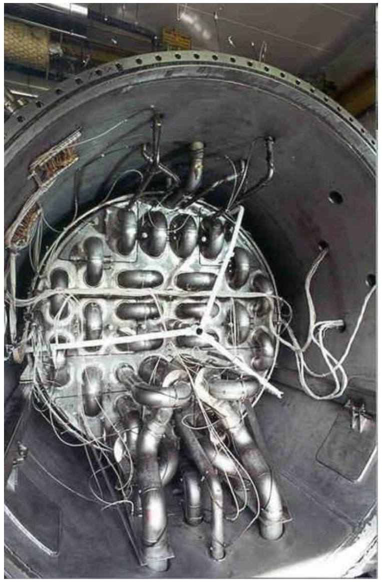


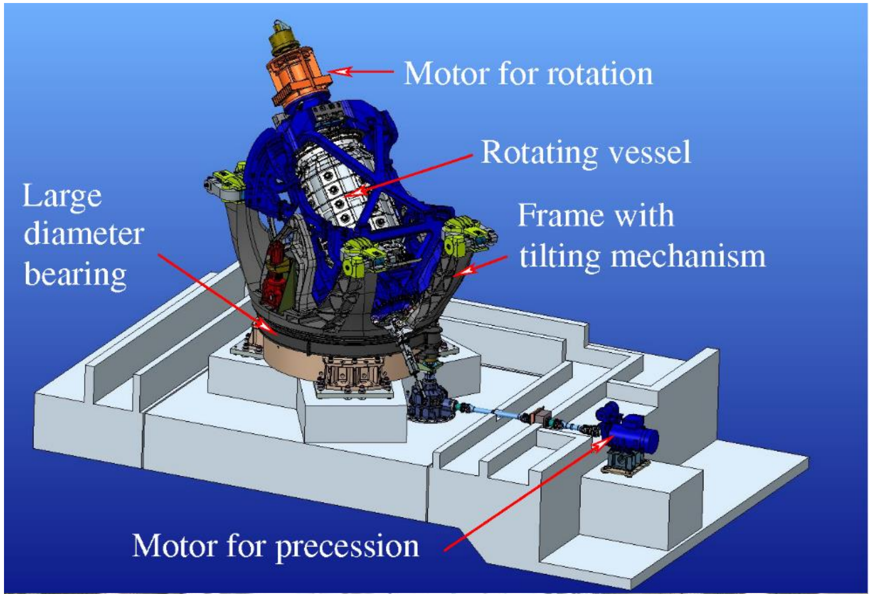
1 – Propeller
2 – Helical sodium flow
3 – Back flow
4 – Sodium at rest
5 – Thermal insulation

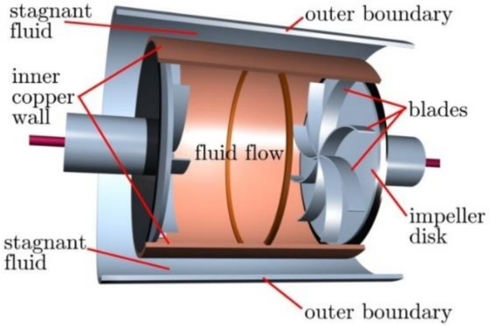
Dynamo module

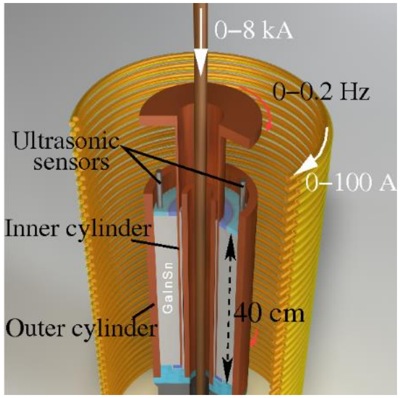


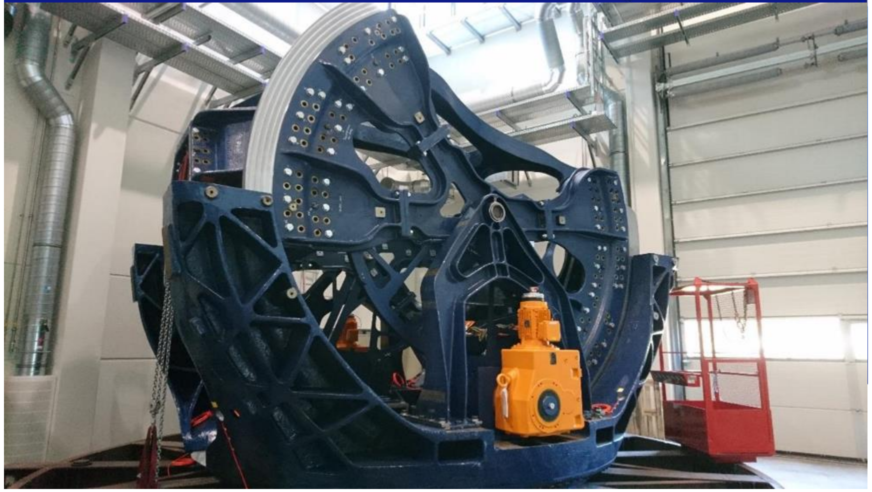
Simulated eigenfield











Schwabe, Hale

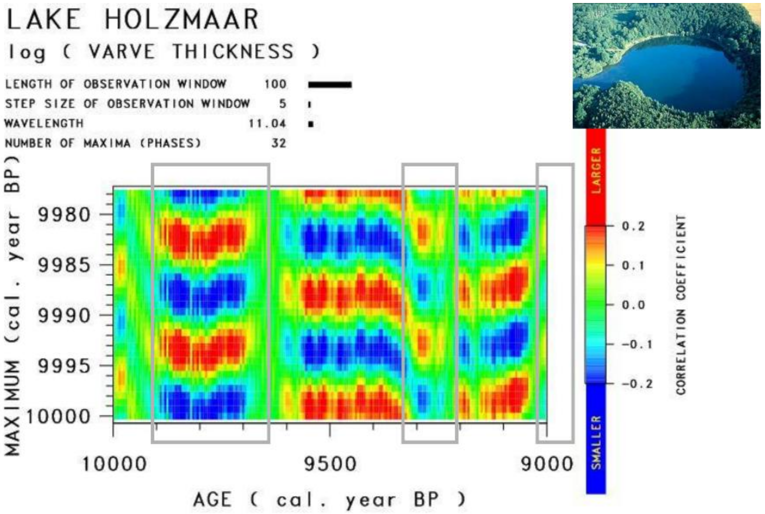
Appetizer: Evidence for phase-stable solar cycle in early Holocene

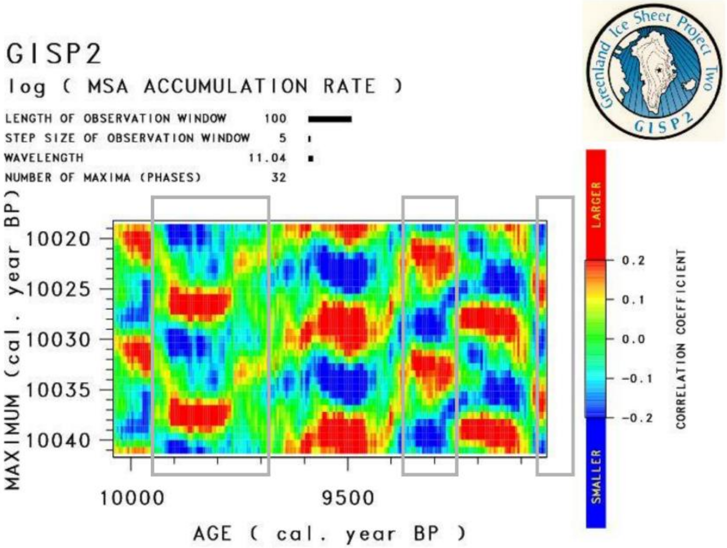
Phase diagrams for algae data from lake Holzmaar und algae-produced Methanesulfonate (MSA) in Greenland ice core GISP2 show 11.04-years cycle with very similar band structures.

Bands are separated by apparent 5.5-years-phase jumps, resulting from nonlinear transfer function (due to optimality condition of algae growth)

Strong evidence for a 11.04-years-cycle, that was phase-stable over 1000 years!

Vos et al., in “Climate in Historical Times: Towards a Synthesis of Holocene Proxy Data and Climate Models”, GKSS School of Environmental Research, p. 293

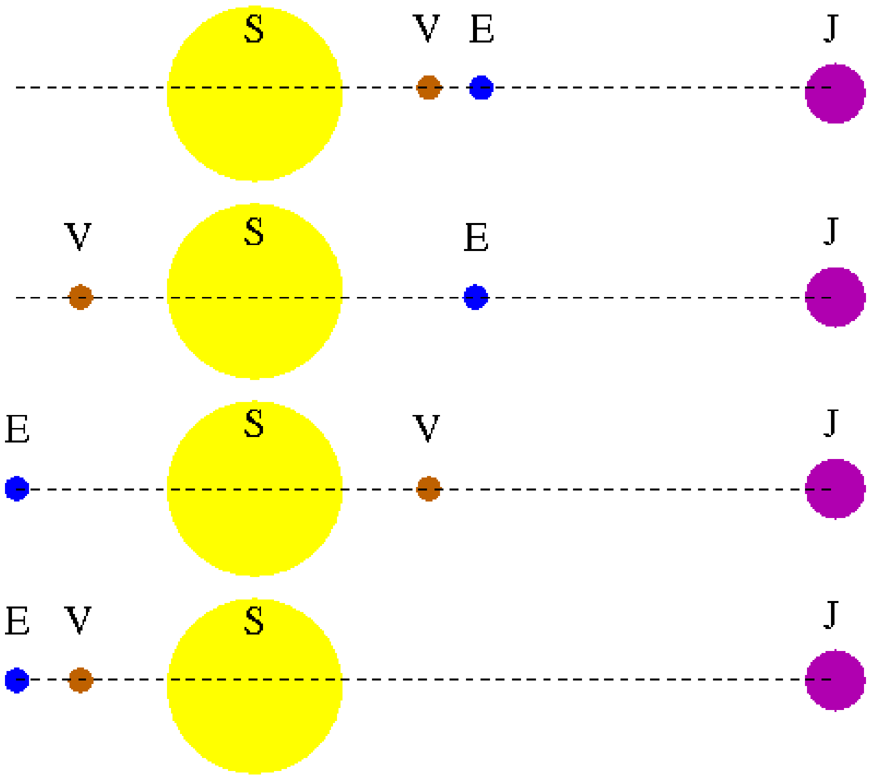




Stefani, Beer, Giesecke et al., Astronomische Nachrichten, doi:10.1002/asna.202013809

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!)



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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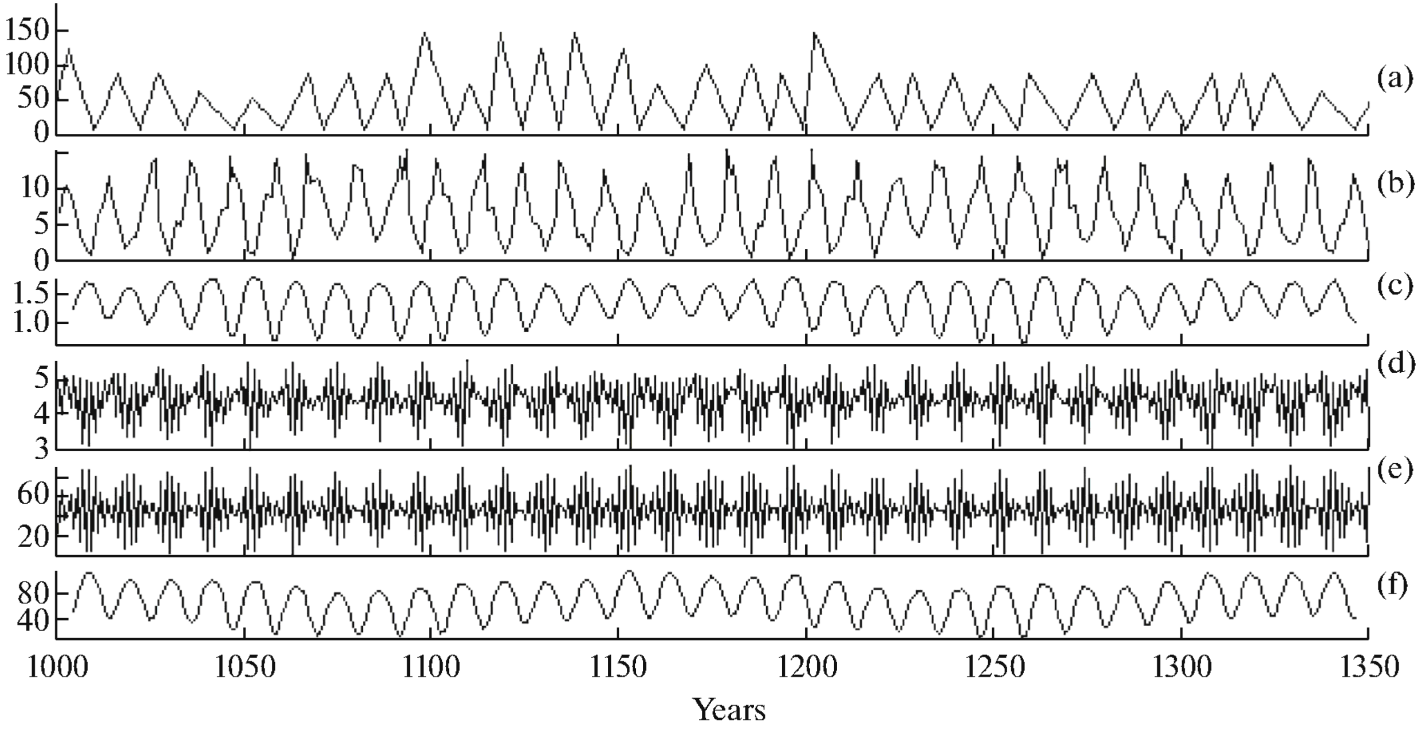
Sunspots

VEJ index



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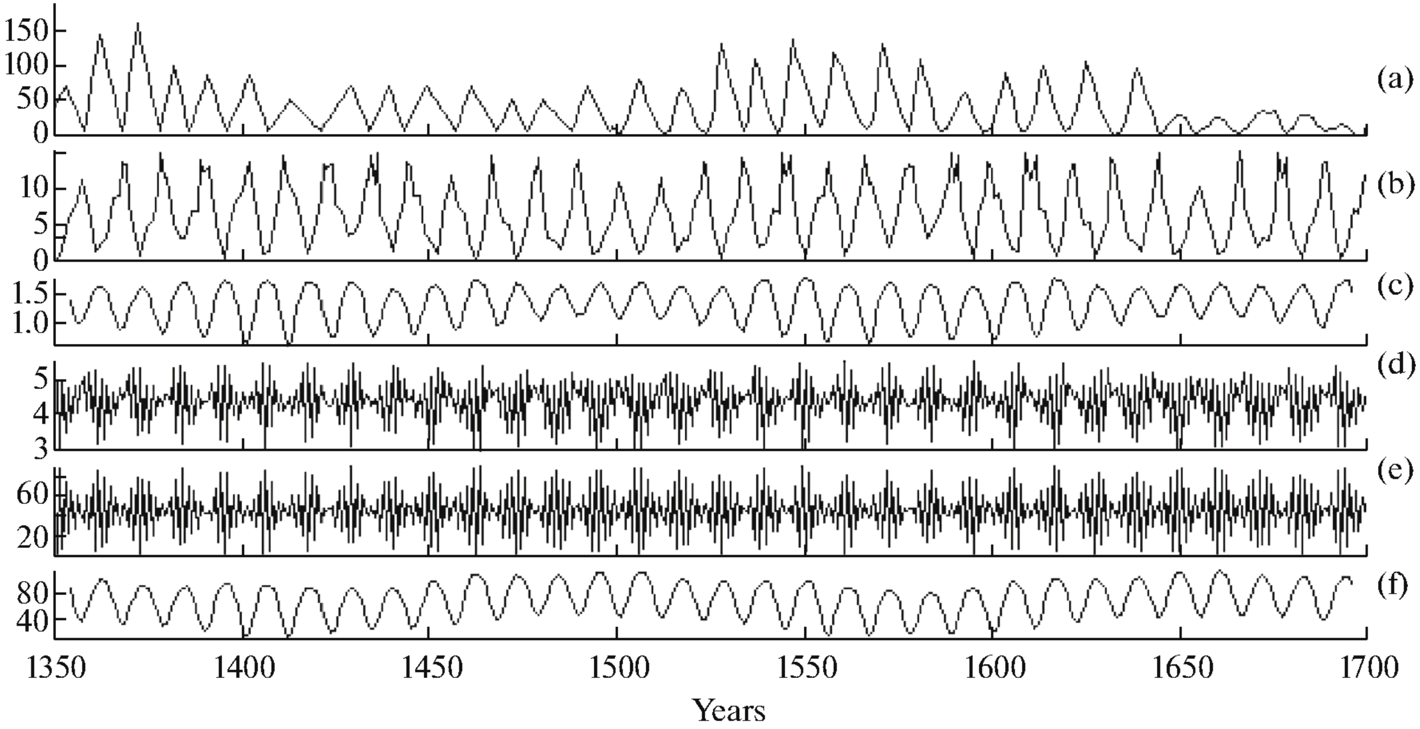

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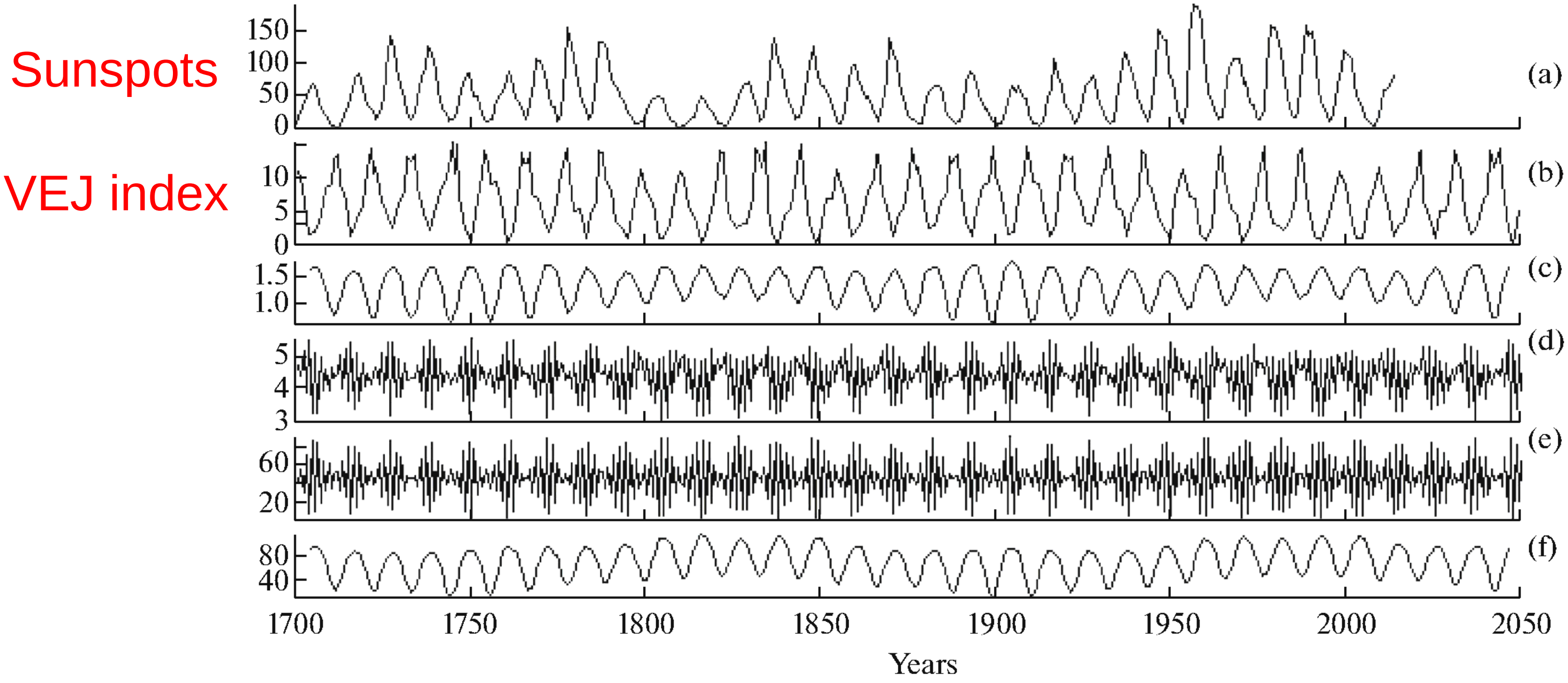

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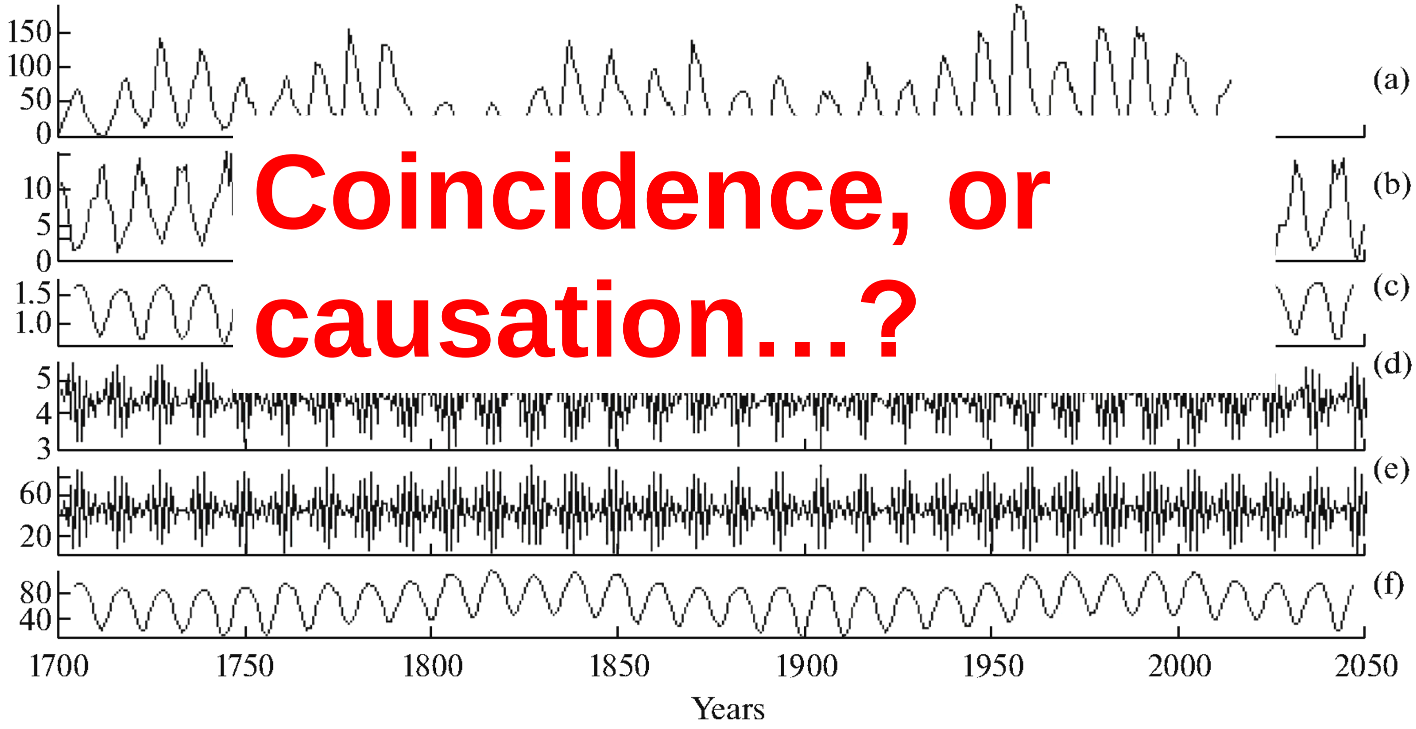


Sunspots

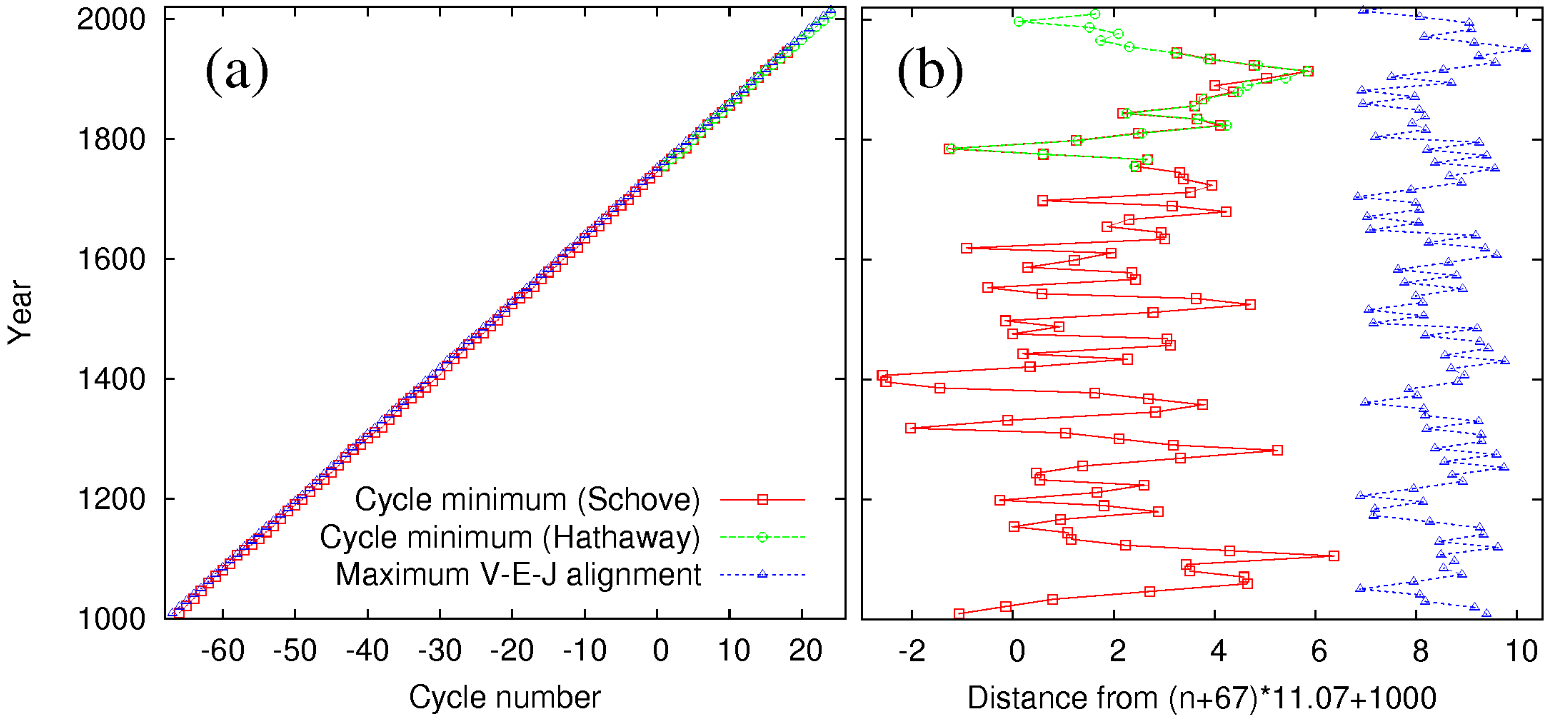
VEJ index

Coincidence, or causation…?

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

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., Solar Physics 294 (2019), 60

Schove´s maxima with and without “lost cycles”

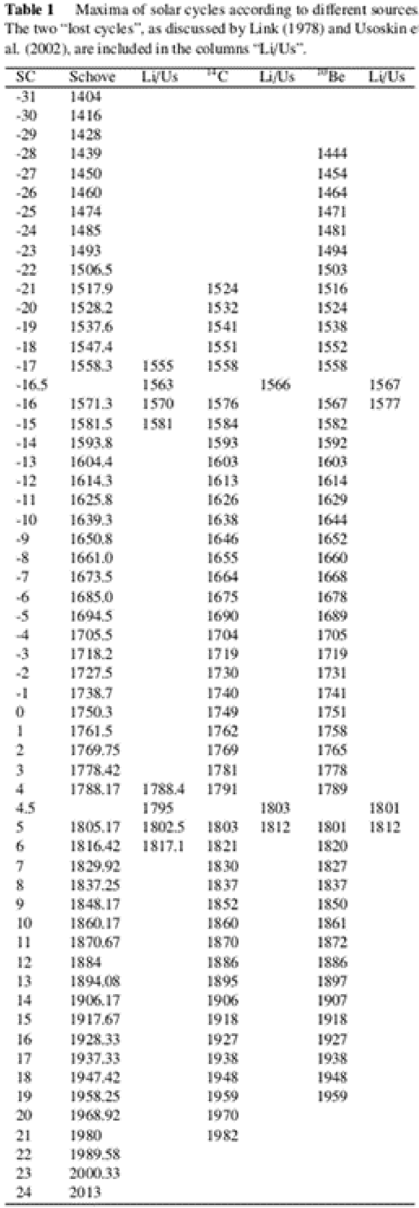
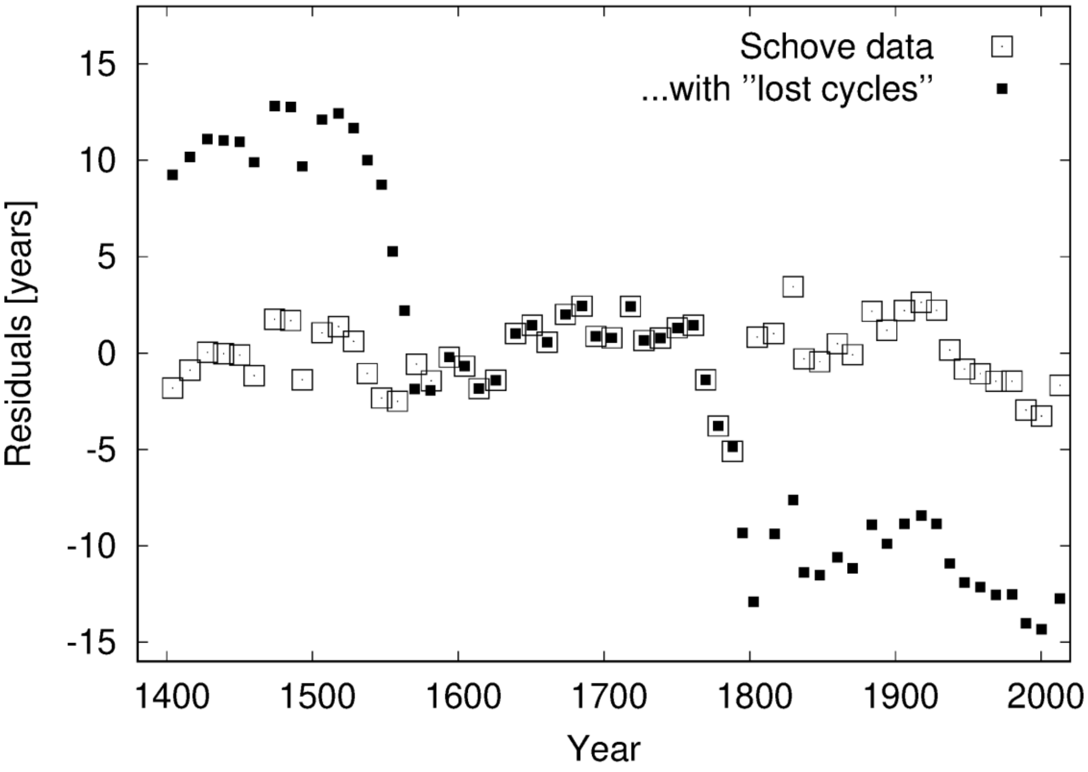


Table 1 Maxima of solar cycles according to different sources. The two “lost cycles”, as discussed by Link (1978) and Usoskin et al. (2002), are included in the columns “Li/Us”.

SC	Schove	Li/Us	^{14}C	Li/Us	^{10}Be	Li/Us
-31	1404					
-30	1416					
-29	1428					
-28	1439				1444	
-27	1450				1454	
-26	1460				1464	
-25	1474				1471	
-24	1485				1481	
-23	1493				1494	
-22	1506.5				1503	
-21	1517.9		1524		1516	
-20	1528.2		1532		1524	
-19	1537.6		1541		1538	
-18	1547.4		1551		1552	
-17	1558.3	1555	1558		1558	
-16.5		1563		1566		1567
-16	1571.3	1570	1576		1567	1577
-15	1581.5	1581	1584		1582	
-14	1593.8		1593		1592	
-13	1604.4		1603		1603	
-12	1614.3		1613		1614	
-11	1625.8		1626		1629	
-10	1639.3		1638		1644	
-9	1650.8		1646		1652	
-8	1661.0		1655		1660	
-7	1673.5		1664		1668	
-6	1685.0		1675		1678	
-5	1694.5		1690		1689	
-4	1705.5		1704		1705	
-3	1718.2		1719		1719	
-2	1727.5		1730		1731	
-1	1738.7		1740		1741	
0	1750.3		1749		1751	
1	1761.5		1762		1758	
2	1769.75		1769		1765	
3	1778.42		1781		1778	
4	1788.17	1788.4	1791		1789	
4.5		1795		1803		1801
5	1805.17	1802.5	1803	1812	1801	1812
6	1816.42	1817.1	1821		1820	
7	1829.92		1830		1827	
8	1837.25		1837		1837	
9	1848.17		1852		1850	
10	1860.17		1860		1861	
11	1870.67		1870		1872	
12	1884		1886		1886	
13	1894.08		1895		1897	
14	1906.17		1906		1907	
15	1917.67		1918		1918	
16	1928.33		1927		1927	
17	1937.33		1938		1938	
18	1947.42		1948		1948	
19	1958.25		1959		1959	
20	1968.92		1970			
21	1980		1982			
22	1989.58					
23	2000.33					
24	2013					

Residuals from 11.07-years-trend (O-C), without and with considering „lost cycles“



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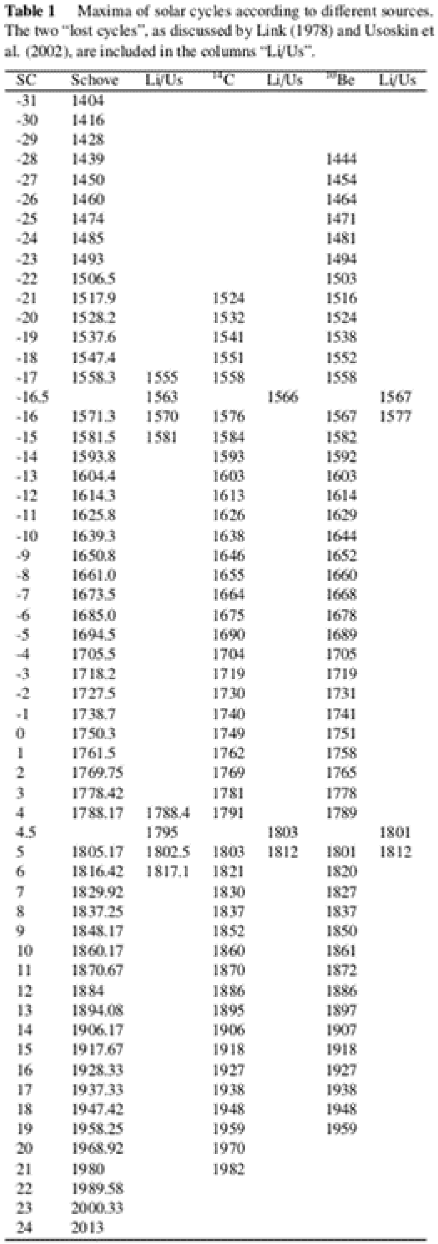

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-17	1558.3	1555	1558		1558	
-16.5		1563		1566		1567
-16	1571.3	1570	1576		1567	1577
-15	1581.5	1581	1584		1582	
-14	1593.8		1593		1592	
-13	1604.4		1603		1603	
-12	1614.3		1613		1614	
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16	1928.33		1927		1927	
17	1937.33		1938		1938	
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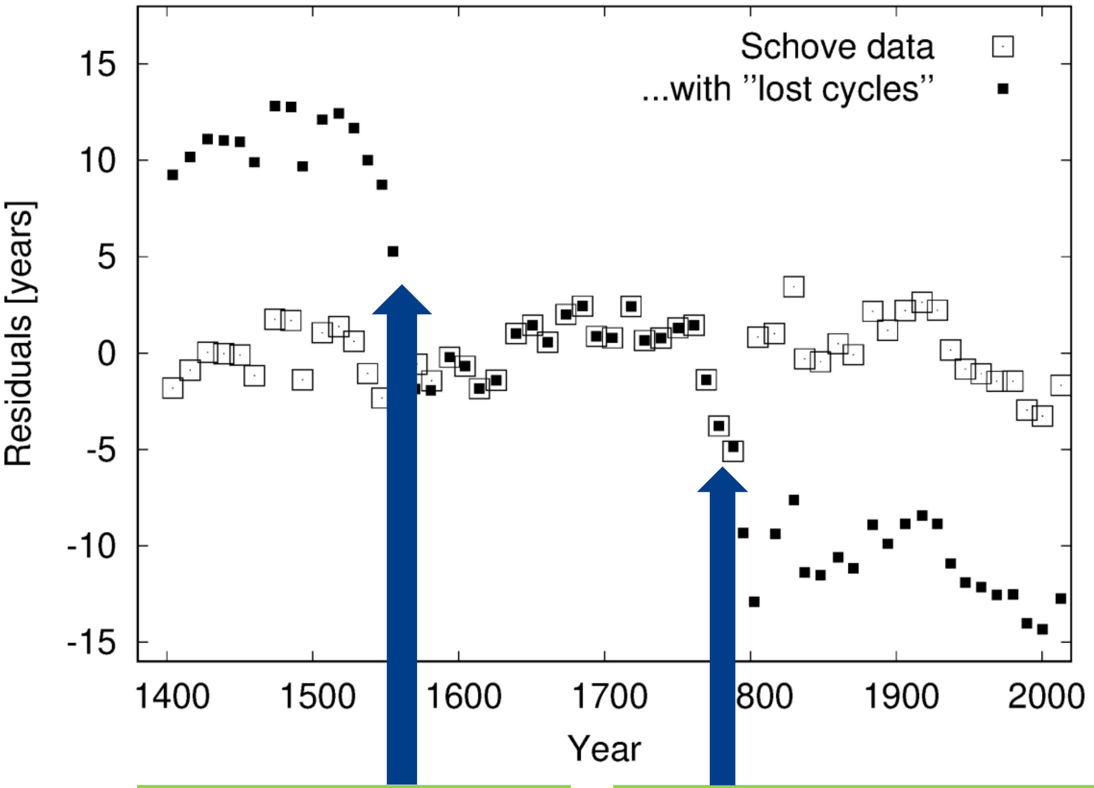
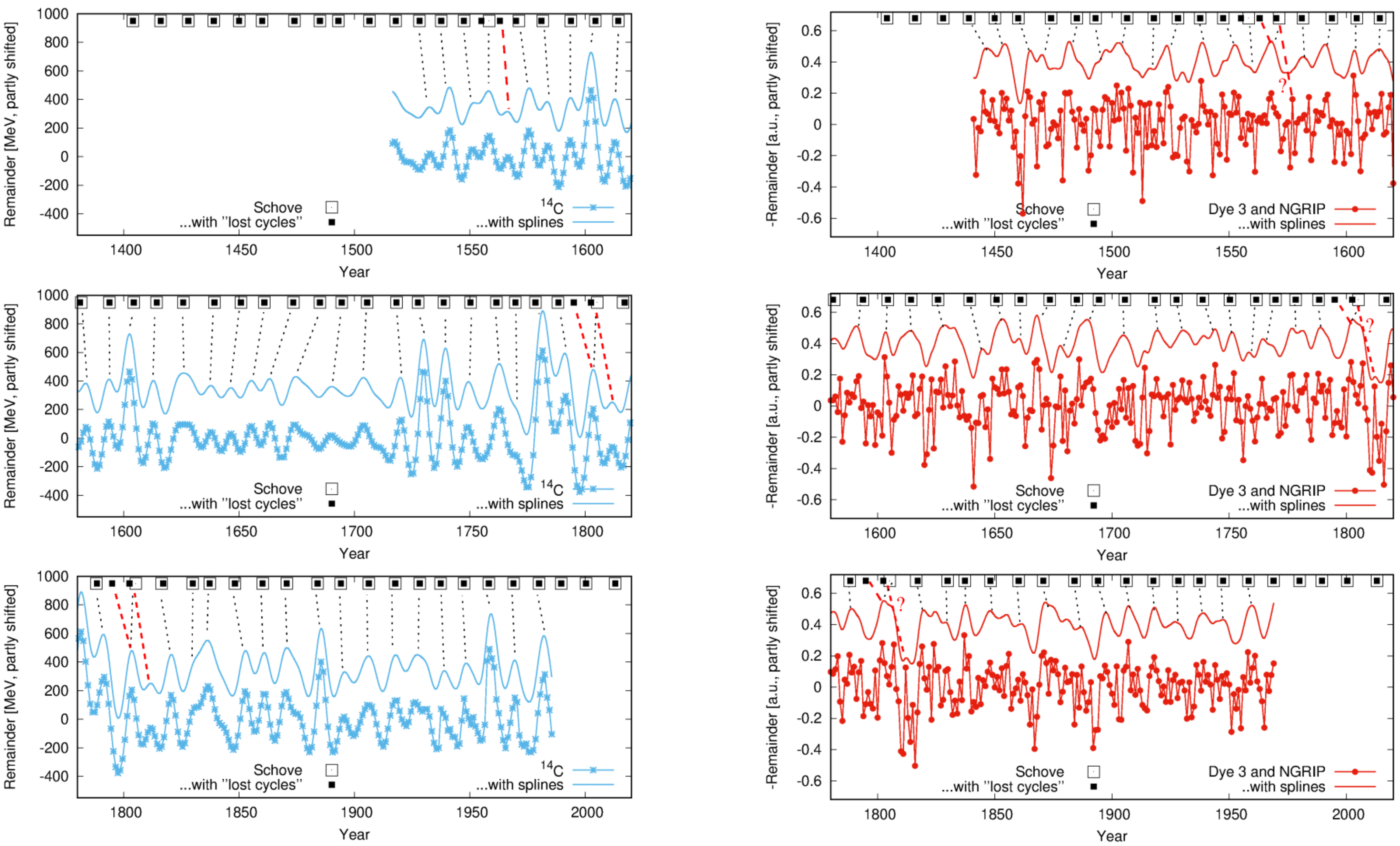


Link, Sol. Phys., 59 (1978), 175

Usoskin et al., Geophys. Res. Lett. 29 (2002), 2183.

Stefani, Beer, Giesecke et al., Astronomische Nachrichten, doi:10.1002/asna.202013809

Comparison of ^{14}C and ^{10}Be Data with Schove's maxima-Data



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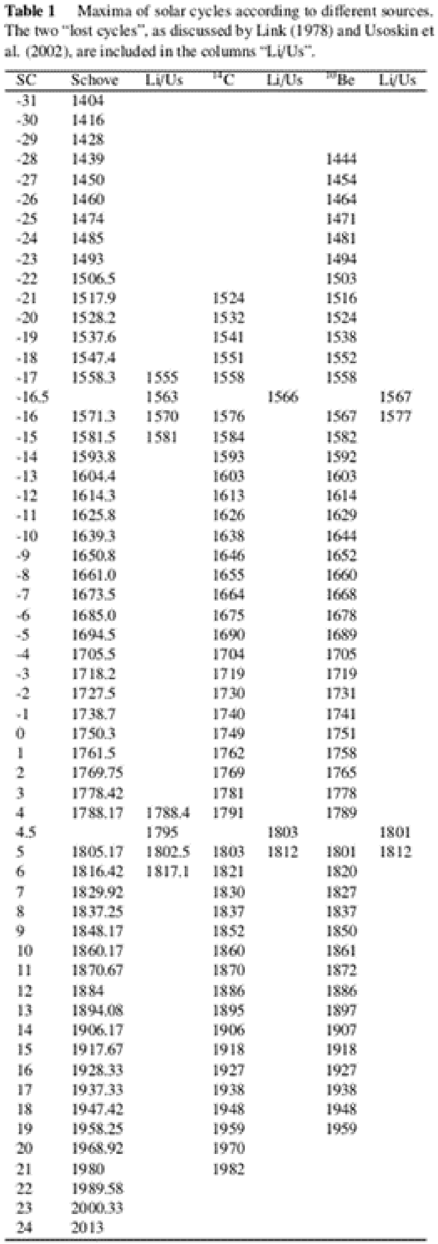
Schove´s, ^{14}C, and ^{10}Be maxima with and without “lost cycles”



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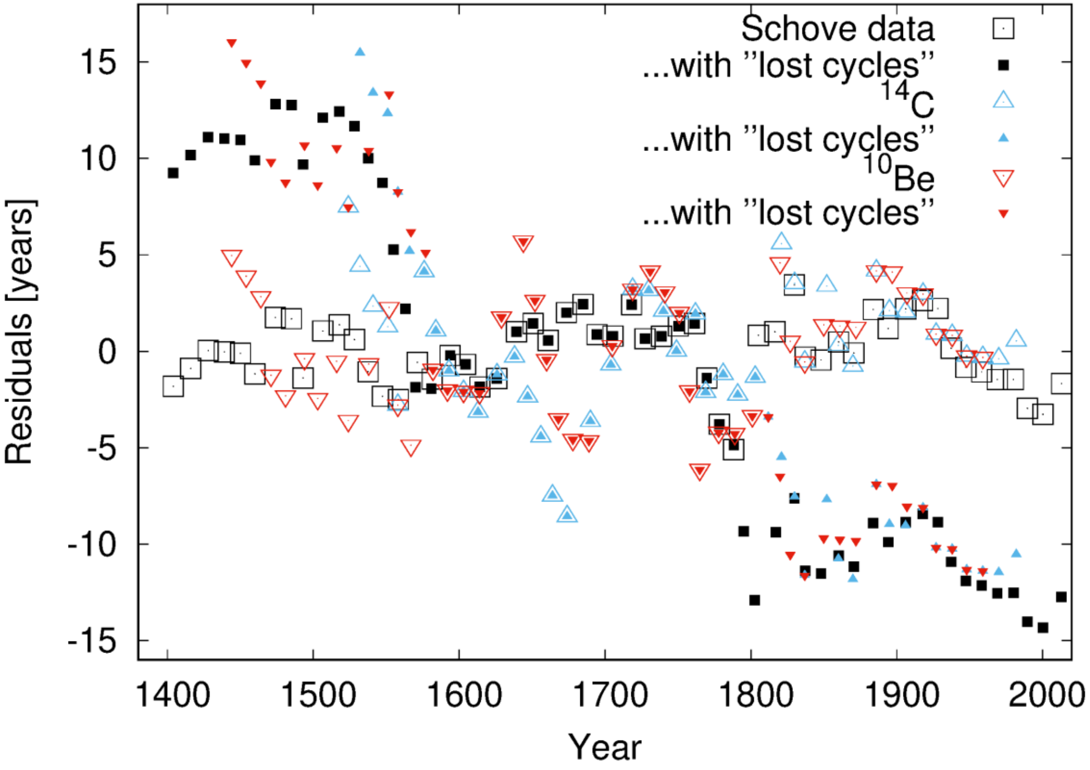
24	2013					

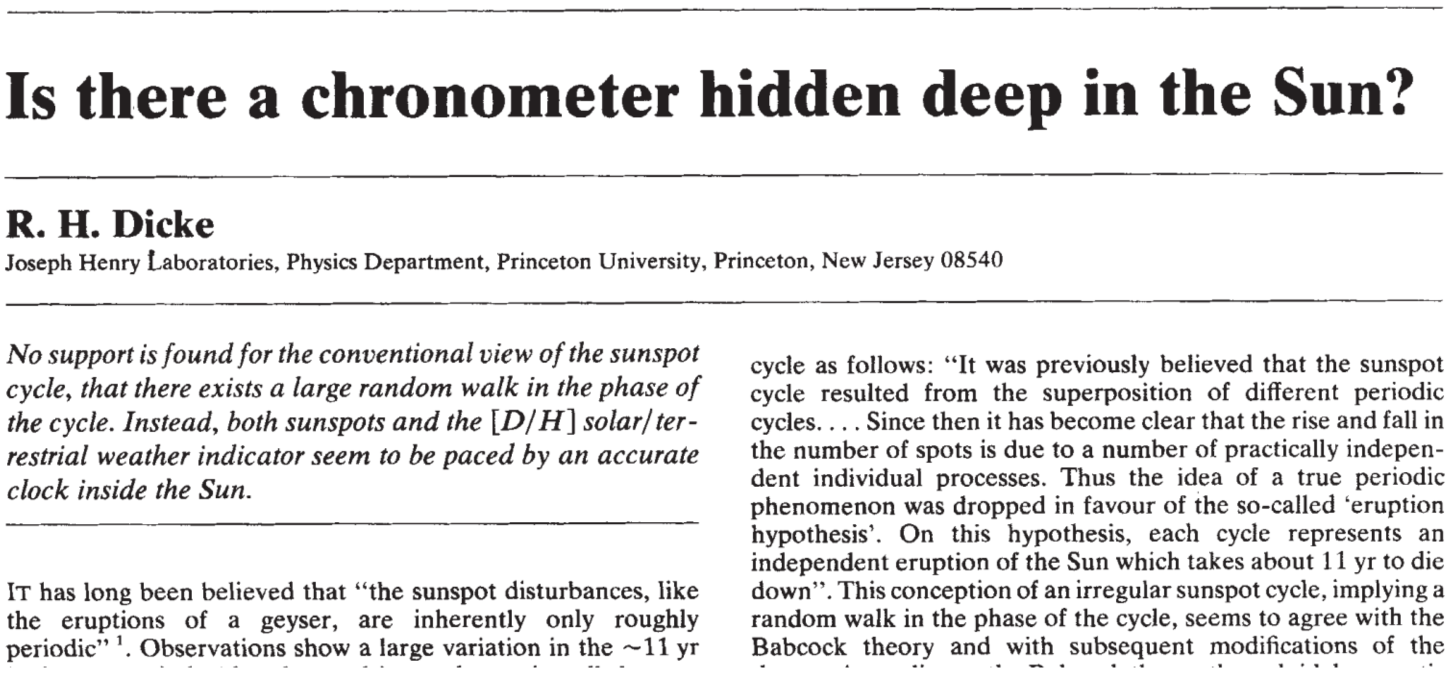
Residuals from 11.07-years-trend (O-C), without and with considering „lost cycles“



Stefani, Beer, Giesecke et al., Astronomische Nachrichten, doi:10.1002/asna.202013809

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

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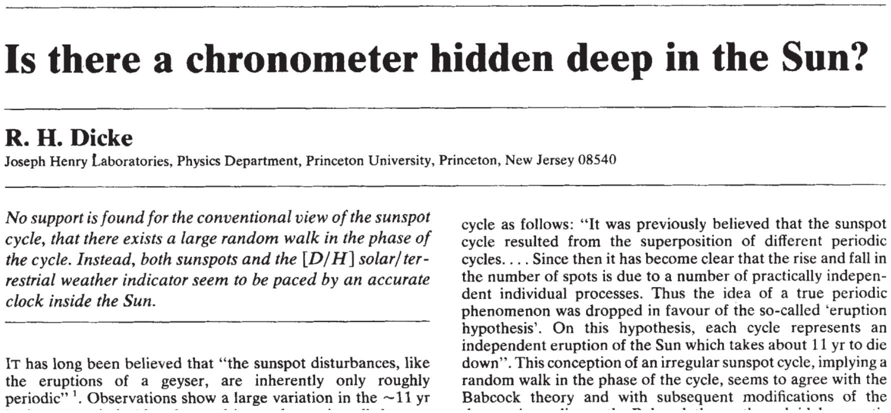
IT has long been believed that "the sunspot disturbances, like the eruptions of a geyser, are inherently only roughly periodic"[1]. Observations show a large variation in the ~11 yr

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

Dicke´s argument



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

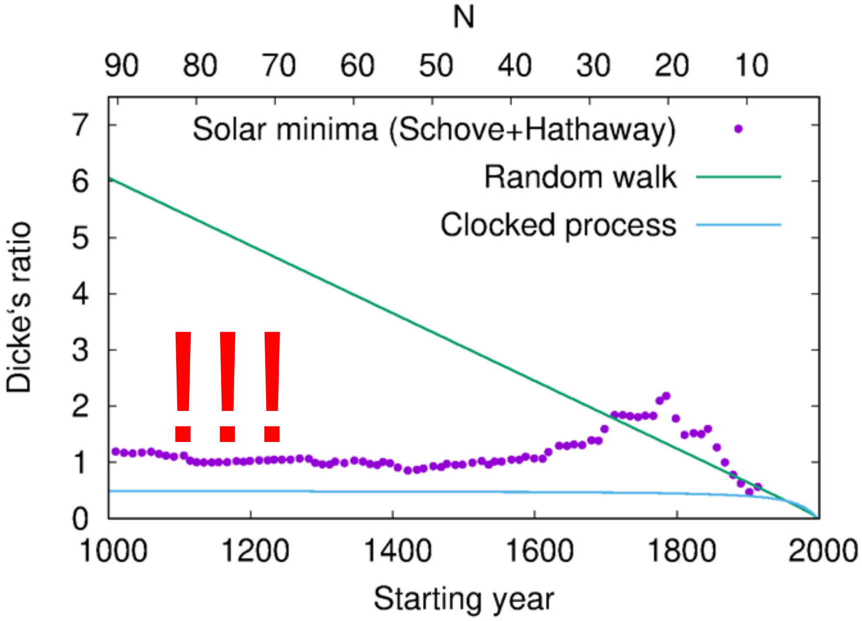
Distinction between random walk (RW) and clocked process (CP) for the instants y_n of sunspot maxima (Dicke) or minima (here):

Residuals: $\delta y_n = y_n - y_0 - p(n-1)$,
with p being the mean cycle period

A telling measure for discriminating between RW und CP is the RATIO between the mean square of δy_n and the mean square of $(\delta y_n - \delta y_{n-1})$

	RATIO	Limes N→ infinity
Random walk	$(N+1)(N^2-1)/3(5N^2+6N-3)$	N/15
Clocked process	$(N^2-1)/2(N^2+2N+3)$	1/2

Dicke´s ratio in dependence on number of cycles



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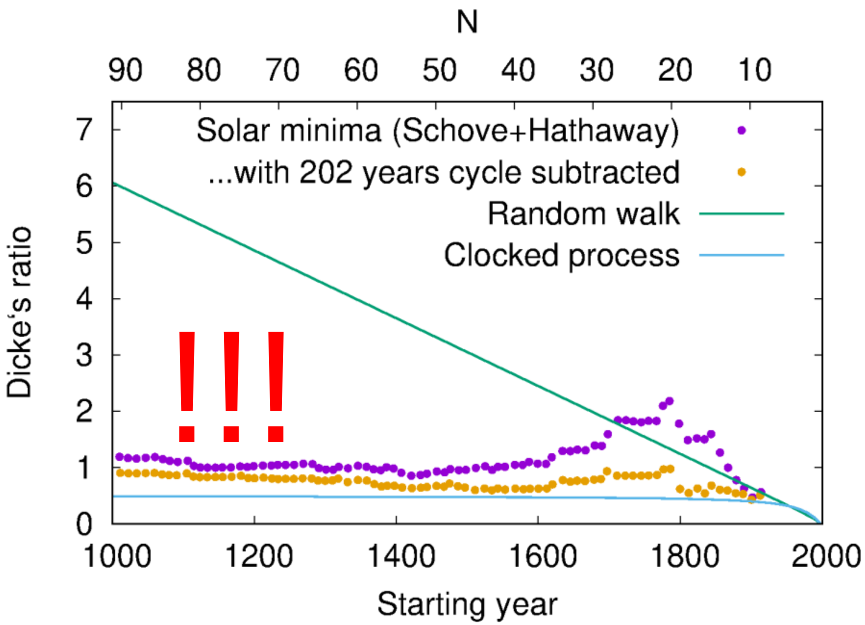

- After subtraction of Suess/de Vries cycle, Dicke's ratio fits nearly perfectly to a CP

Distinction between random walk (RW) and clocked process (CP) for the instants y_n of sunspot maxima (Dicke) or minima (here):

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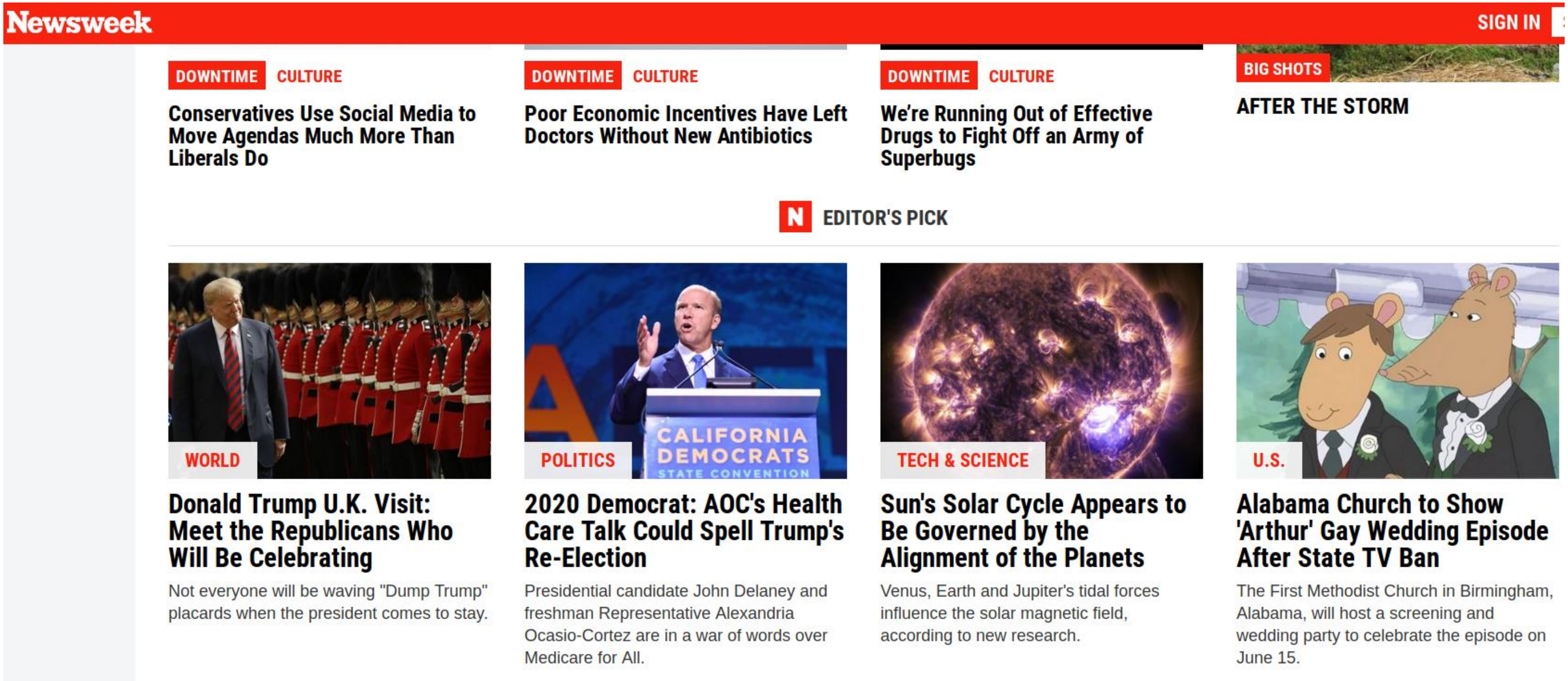
Stefani et al., Solar Physics 294 (2019), 60

Presse coverage: Newsweek of 4 June, 2019, Editor‘s pick



DOWNTIME CULTURE

Conservatives Use Social Media to Move Agendas Much More Than Liberals Do

DOWNTIME CULTURE

Poor Economic Incentives Have Left Doctors Without New Antibiotics

DOWNTIME CULTURE

We're Running Out of Effective Drugs to Fight Off an Army of Superbugs

BIG SHOTS

AFTER THE STORM

N EDITOR'S PICK

WORLD

Donald Trump U.K. Visit: Meet the Republicans Who Will Be Celebrating

Not everyone will be waving "Dump Trump" placards when the president comes to stay.

POLITICS

2020 Democrat: AOC's Health Care Talk Could Spell Trump's Re-Election

Presidential candidate John Delaney and freshman Representative Alexandria Ocasio-Cortez are in a war of words over Medicare for All.

TECH & SCIENCE

Sun's Solar Cycle Appears to Be Governed by the Alignment of the Planets

Venus, Earth and Jupiter's tidal forces influence the solar magnetic field, according to new research.

U.S.

Alabama Church to Show 'Arthur' Gay Wedding Episode After State TV Ban

The First Methodist Church in Birmingham, Alabama, will host a screening and wedding party to celebrate the episode on June 15.

Donald Trump

Alexandria Ocasio-Cortez

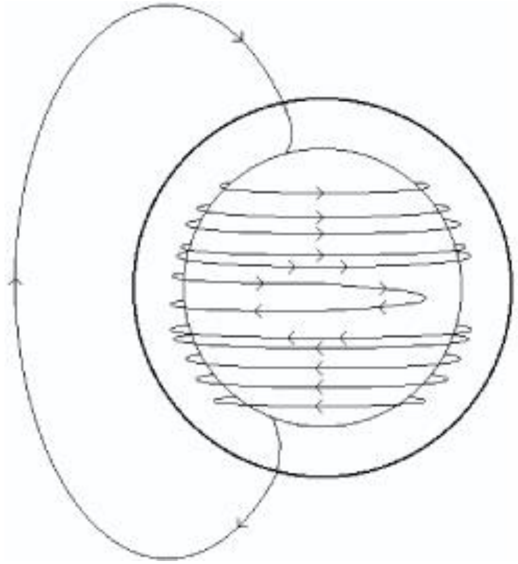
Solar Physics 294 (2019), 60

„Arthur“

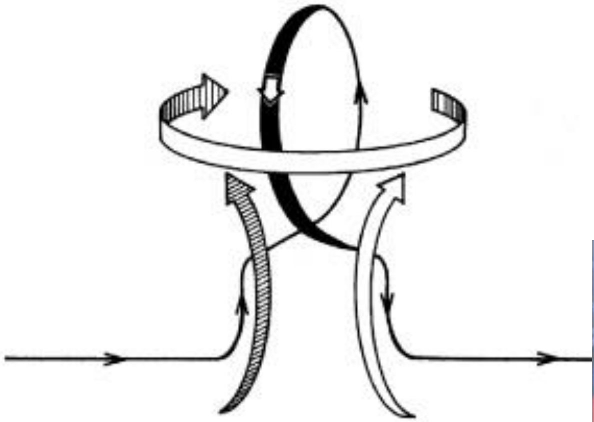
Solar dynamo models: Basics

Any solar dynamo needs:

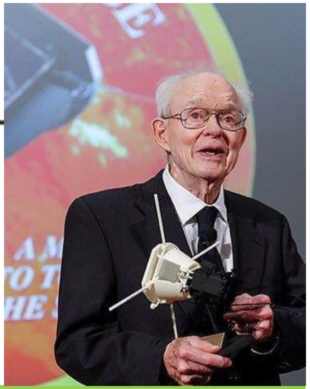
- some Ω effect to regenerate toroidal field from poloidal field
- some α effect to regenerate poloidal field from toroidal field



Ω effect

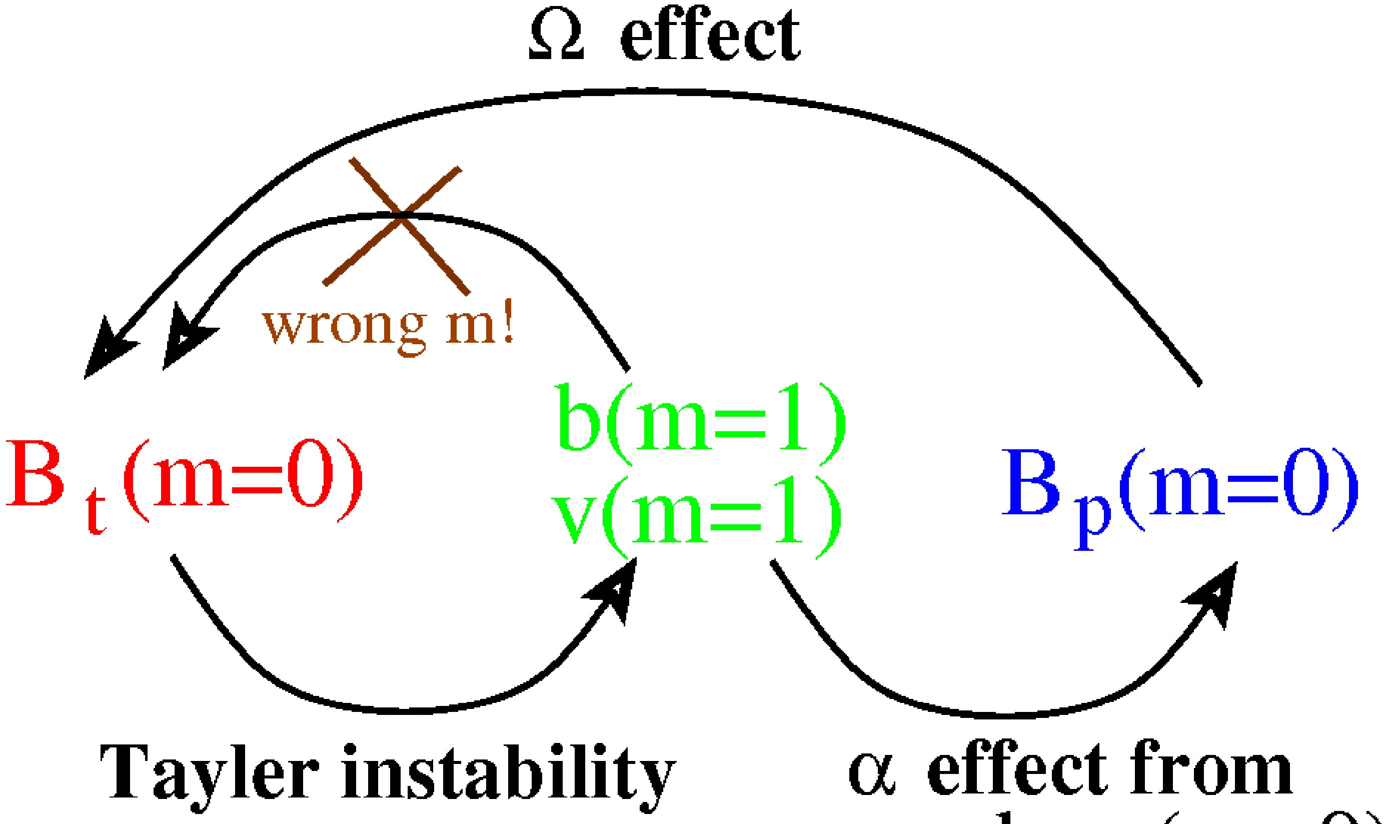


α effect



Parker, Astrophys J. 122, 293 (1955)

Tayler-Spruit dynamo in the solar tachocline: The main problem



Ω effect

wrong m!

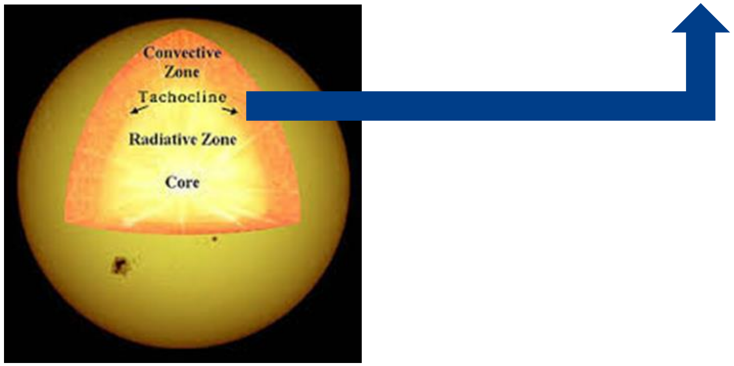
$B_t(m=0)$

$b(m=1)$
$v(m=1)$

$B_p(m=0)$

Tayler instability

α effect from
$< v \times b > (m=0)$

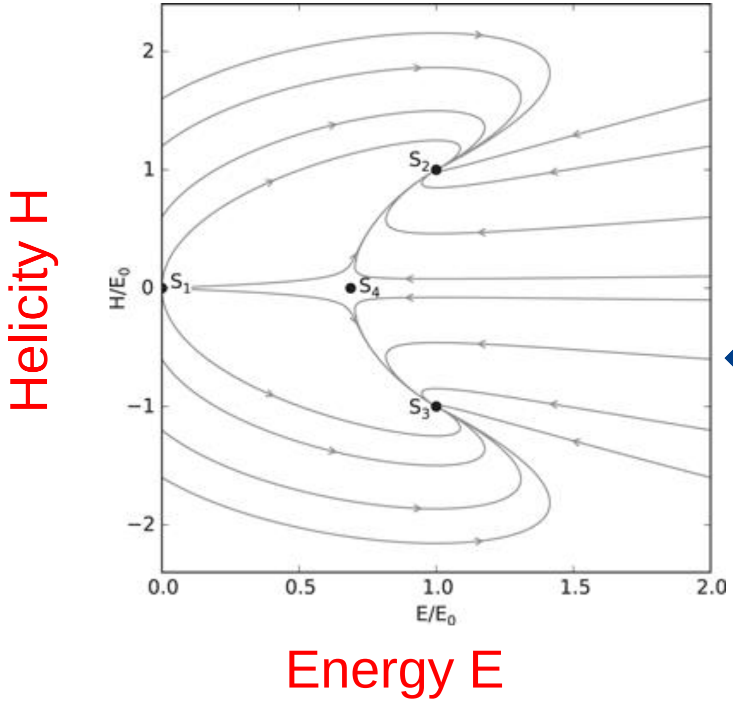


Spruit, Astron. Astrophys. 381 (2002) 923;

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

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

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



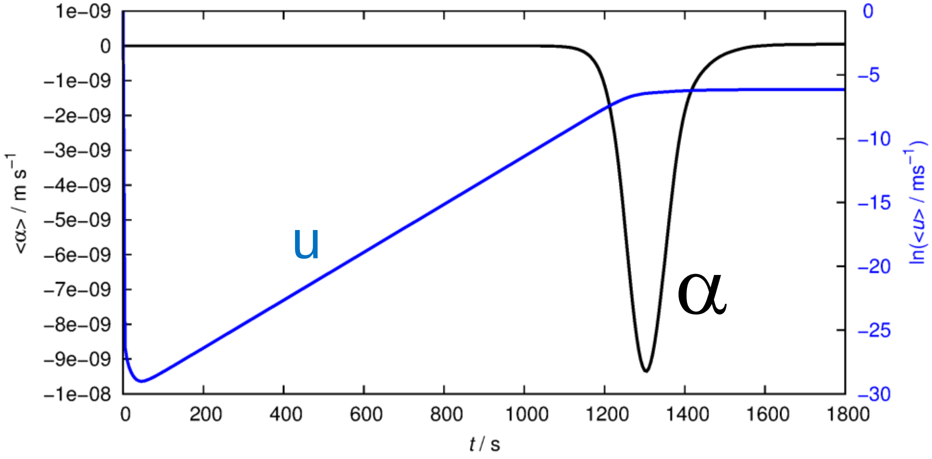
$$\frac{dE}{dt} = 2\gamma E - 2(\mu + \mu_*)E^2 - 2(\mu - \mu_*)H^2$$

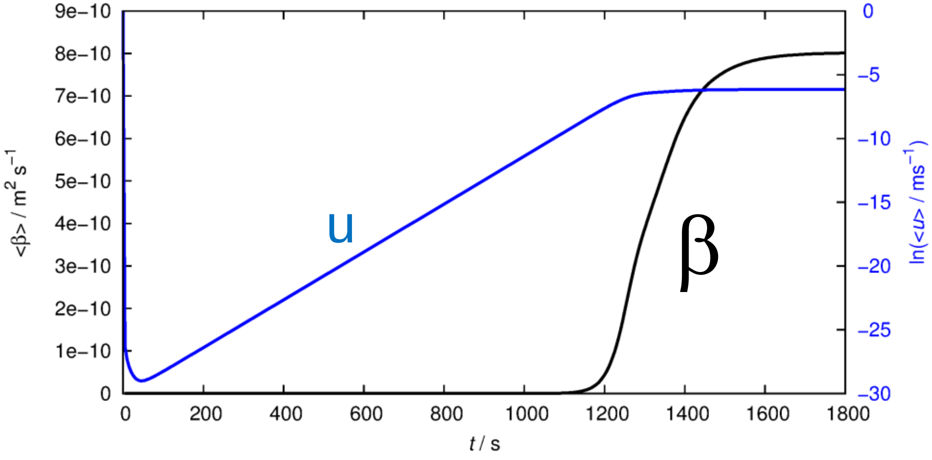
$$\frac{dH}{dt} = 2\gamma H - 4\mu EH$$

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

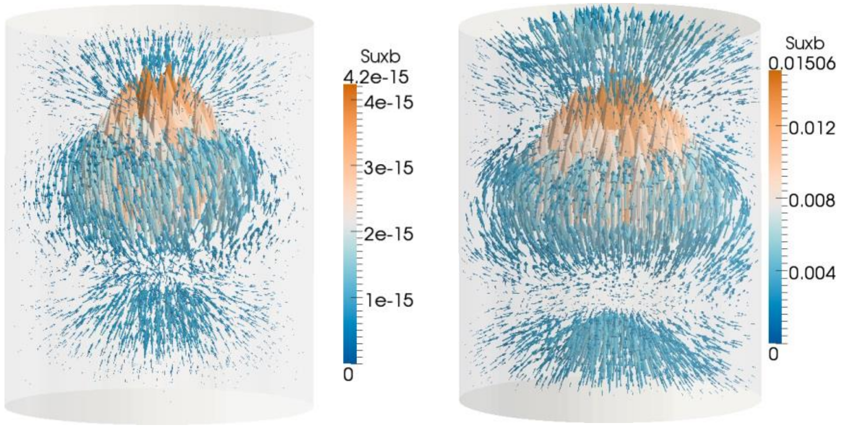
Any helical symmetry breaking at low Pm ?

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

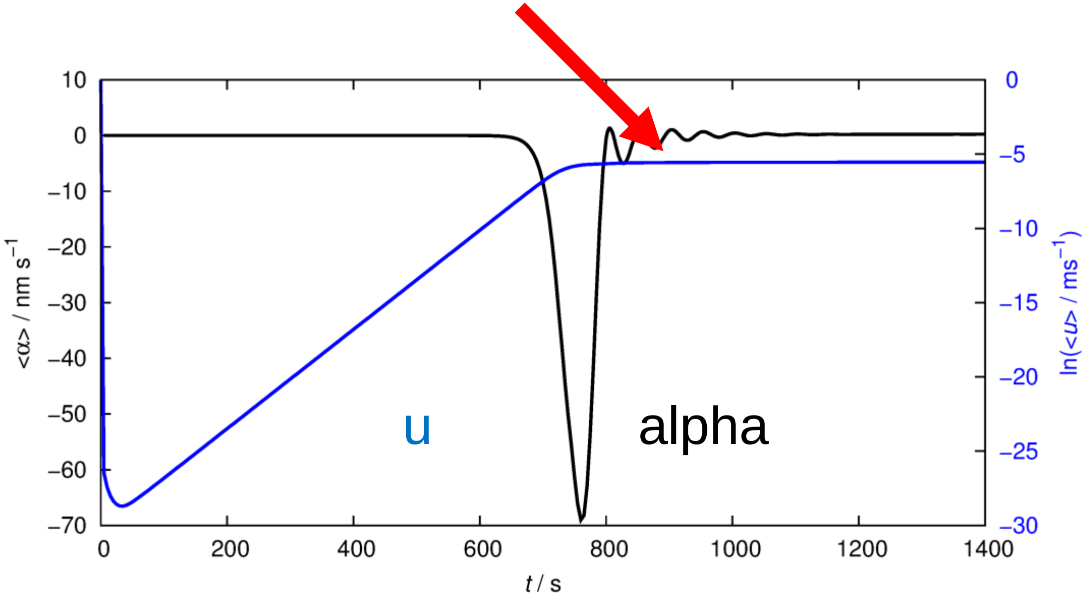
1800 s

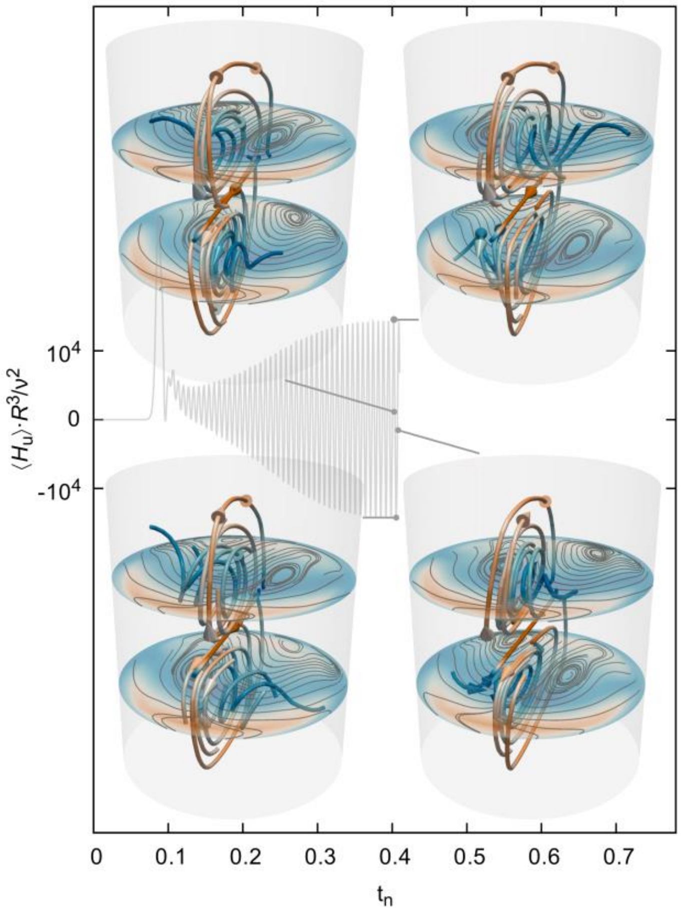
Example: h/d=1.25, Ha=55

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

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

(Damped) helicity oscillations Ha =70

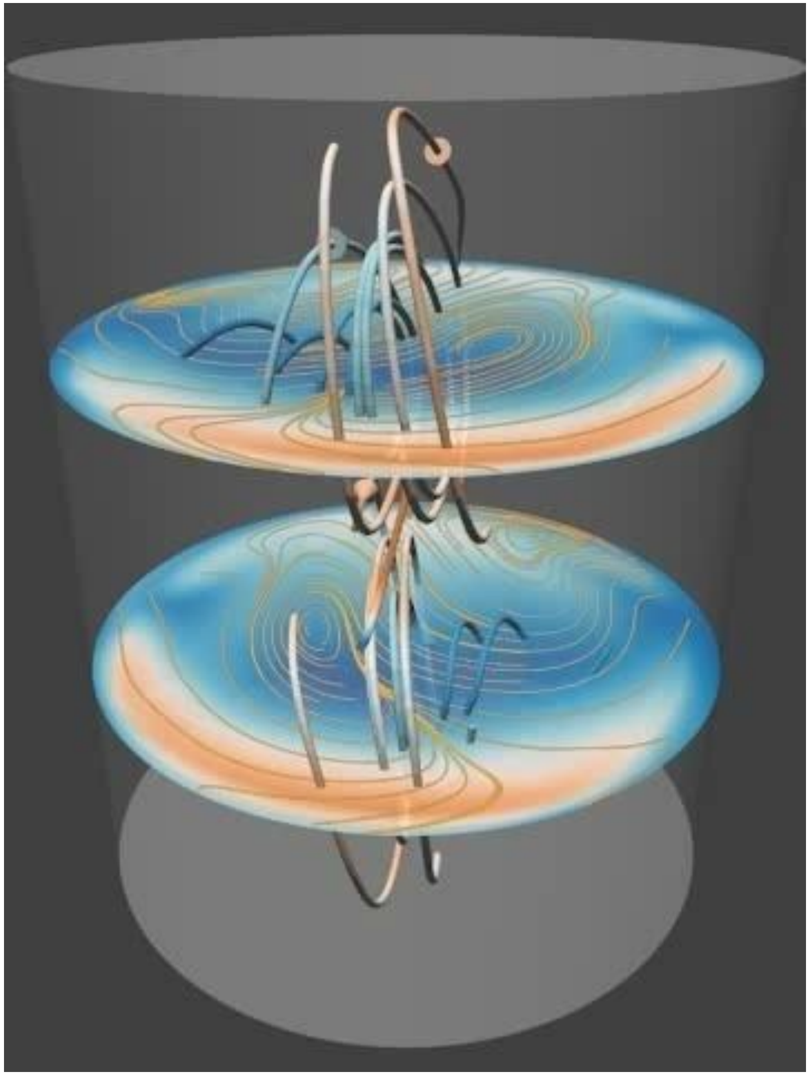




Ha =100

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

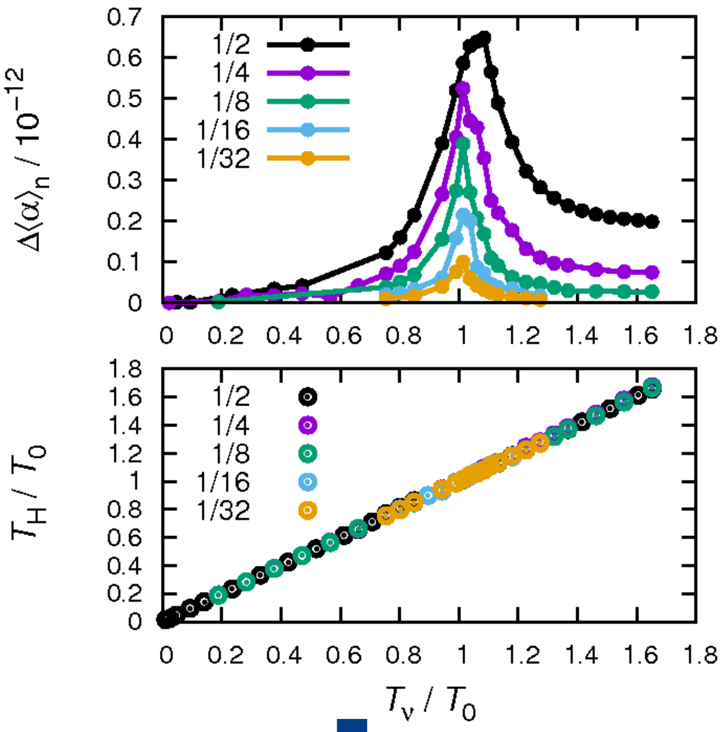
Character of the helicity oscillations

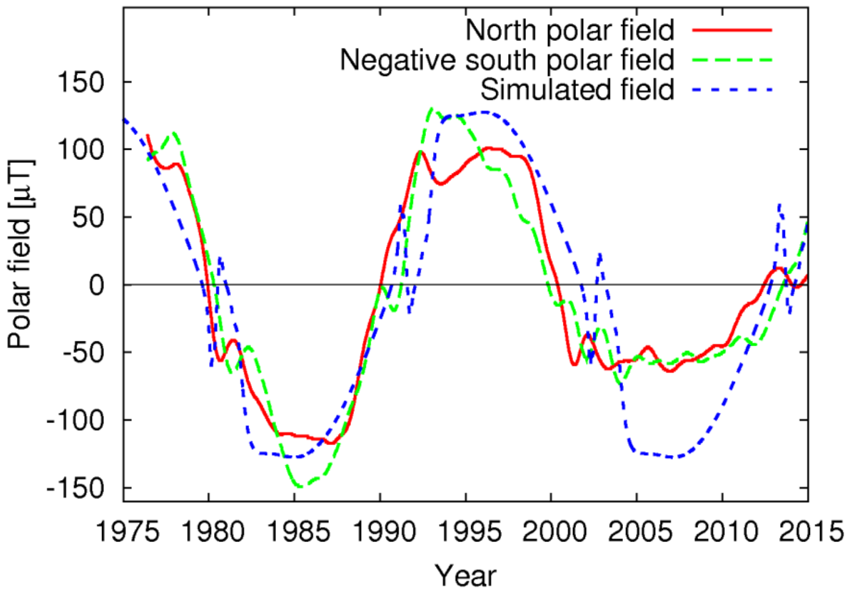


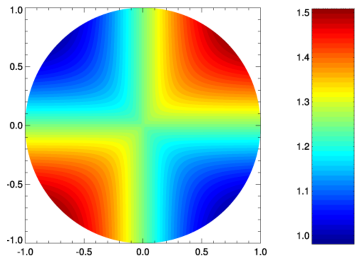
Ha =100
Pm=10^{-6}

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

Modelling the planetary synchronization of the solar dynamo







1:1 synchronization of the helicity of the Tayler instability with tidal (m=2) perturbations (of the VEJ-system?)...

...yields a 22.14 years solar cycle!

Stefani et al, Solar Phys. 291 (2016), 2197

A simple ODE model of a synchronized dynamo

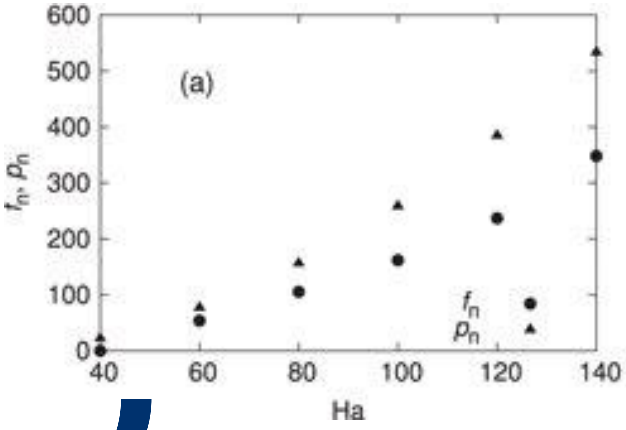
$$\dot{A}(t) = \alpha(t)B(t) - \tau^{-1}A(t)$$

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

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

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

1D-Model (after Parker, but with periodic, synchronized α term):

$$
\begin{aligned}
\frac{\partial B(\theta,t)}{\partial t} &= \omega(\theta,t)\frac{\partial A(\theta,t)}{\partial\theta} - \frac{\partial^2 B(\theta,t)}{\partial\theta^2} - \kappa B^3(\theta,t) \\
\frac{\partial A(\theta,t)}{\partial t} &= \alpha(\theta,t)B(\theta,t) - \frac{\partial^2 A(\theta,t)}{\partial\theta^2},
\end{aligned}
$$

Loss parameter

$$\omega(\theta,t) = \omega_0(1-0.939-0.136\cos^2(\theta)-0.1457\cos^4(\theta))\sin(\theta)\,,$$

$$\alpha(\theta,t) = \alpha^p(\theta,t) + \alpha^c(\theta,t)$$

$$\alpha^p(\theta,t) = \alpha_0^p\sin(2\pi t/11.07)\mathrm{sgn}(90^\circ-\theta)\frac{B^2(\theta,t)}{(1+q_\alpha^p B^4(\theta,t))} \text{ for } 55^\circ<\theta<125^\circ$$

$$\alpha^c(\theta,t) = \alpha_0^c\big(1+\xi(t)\big)\sin(2\theta)/\big(1+q_\alpha^c B^2(\theta,t)\big)$$

Noise with strength D

Stefani et al., Solar Physics 294 (2019), 60

1D-Model (after Parker, but with periodic, synchronized α term):

$$\frac{\partial B(\theta,t)}{\partial t} = \omega(\theta,t)\frac{\partial A(\theta,t)}{\partial \theta} - \frac{\partial^2 B(\theta,t)}{\partial \theta^2} - \kappa B^3(\theta,t)$$

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

Externally **„shaken“**

$$\omega(\theta,t) = \omega_0(1 - 0.939 - 0.136\cos^2(\theta) - 0.1457\cos^4(\theta))\sin(\theta),$$

$$\alpha(\theta,t) = \alpha^p(\theta,t) + \alpha^c(\theta,t)$$

$$\alpha^p(\theta,t) = \alpha_0^p \sin(2\pi t/11.07)\mathrm{sgn}(90^\circ - \theta)\frac{B^2(\theta,t)}{(1+q_\alpha^p B^4(\theta,t))} \text{ for } 55^\circ < \theta < 125^\circ$$

$$\alpha^c(\theta,t) = \alpha_0^c\big(1+\xi(t)\big)\sin(2\theta)/\big(1+q_\alpha^c B^2(\theta,t)\big)$$

Internally **„stirred“**

Stefani et al., Solar Physics 294 (2019), 60

1D-Model (after Parker, but with periodic, synchronized α term):

$$\frac{\partial B(\theta,t)}{\partial t} = \omega(\theta,t)\frac{\partial A(\theta,t)}{\partial \theta} - \frac{\partial^2 B(\theta,t)}{\partial \theta^2} - \kappa B^3(\theta,t)$$

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

$$\omega(\theta,t) = \omega_0(1 - 0.939 - 0.136\cos^2(\theta) - 0.1457\cos^4(\theta))\sin(\theta)\,,$$

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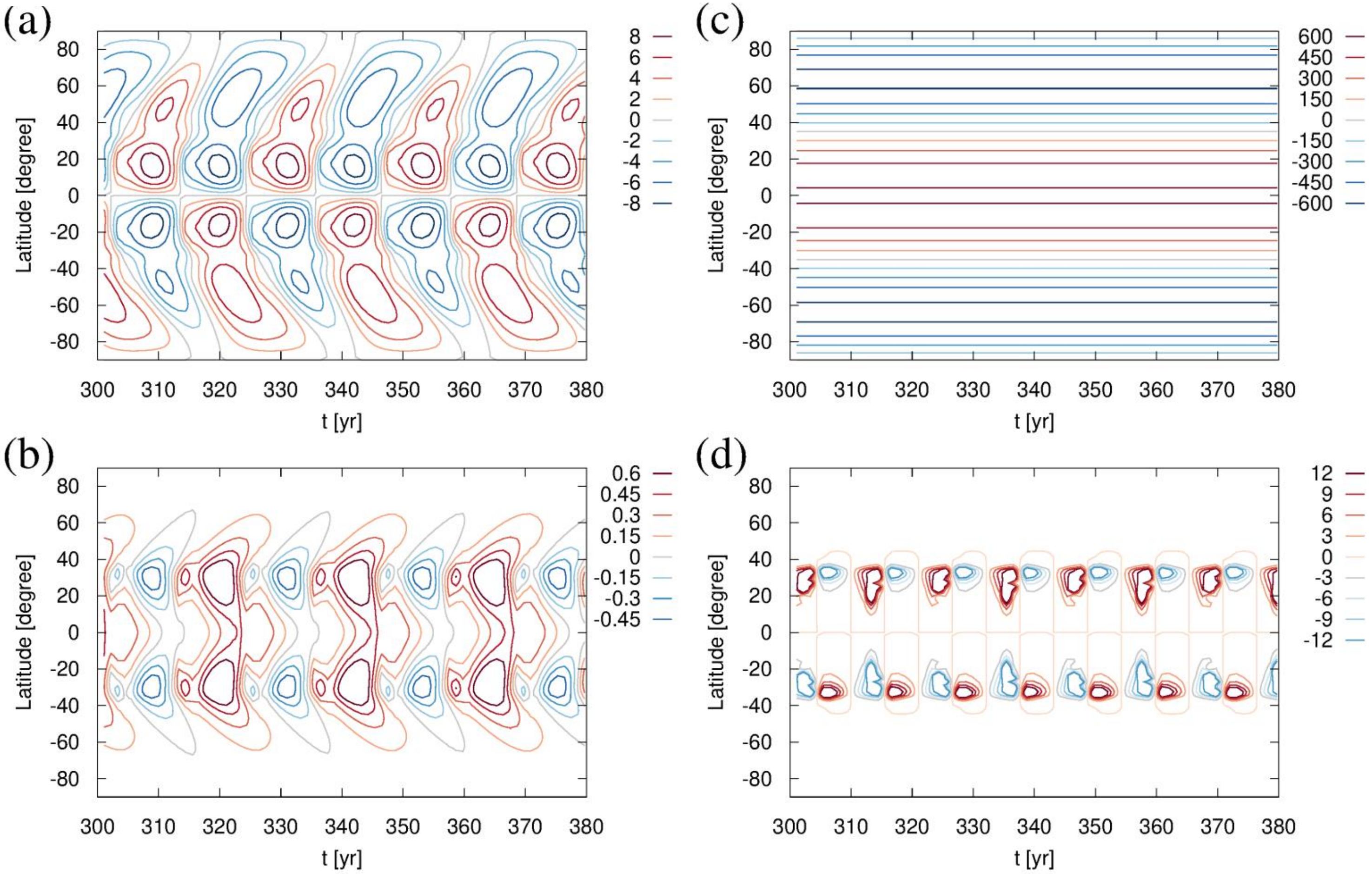
$B(\theta,t)$

$\omega(\theta,t)$



$A(\theta,t)$

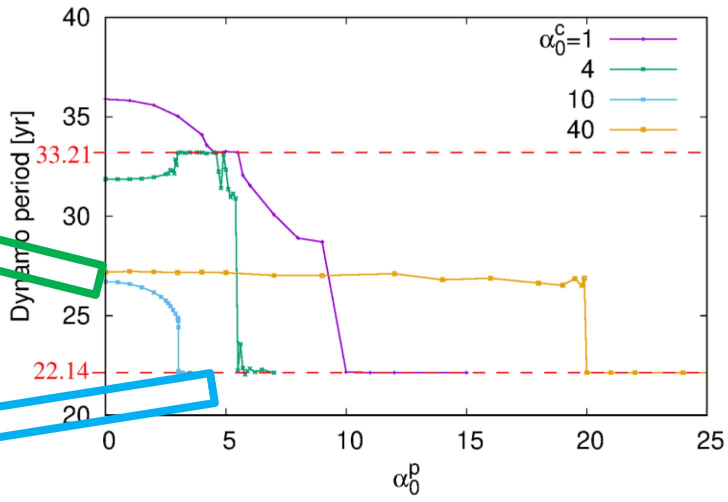
$\alpha(\theta,t)$

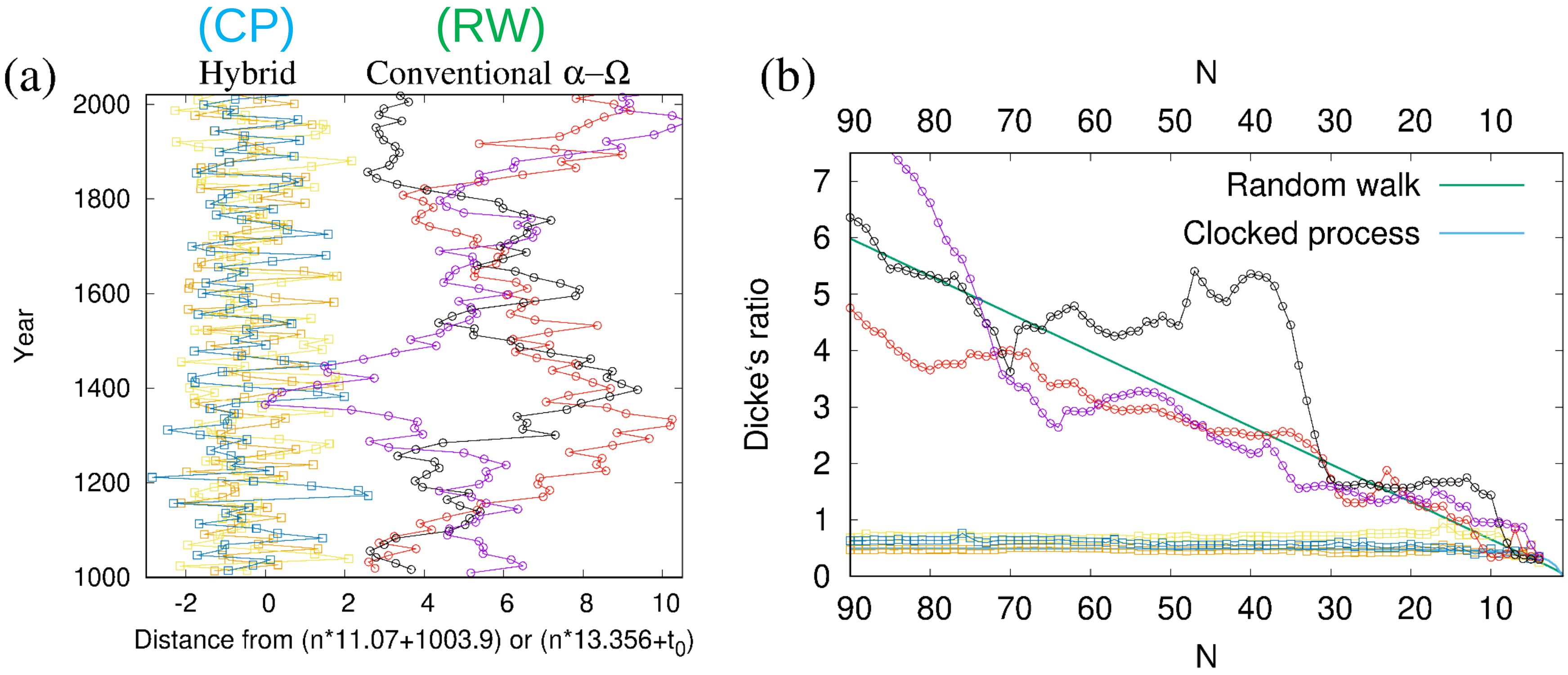
$\omega_0=10000$, $\kappa=0.2$, $q_\alpha^p=0.2$, $\alpha_0^p=100$

1D-Model with Noise

Conventional alpha-Omega dynamo yields random walk (RW)

Synchronized (hybrid) model yields clocked process (CP)



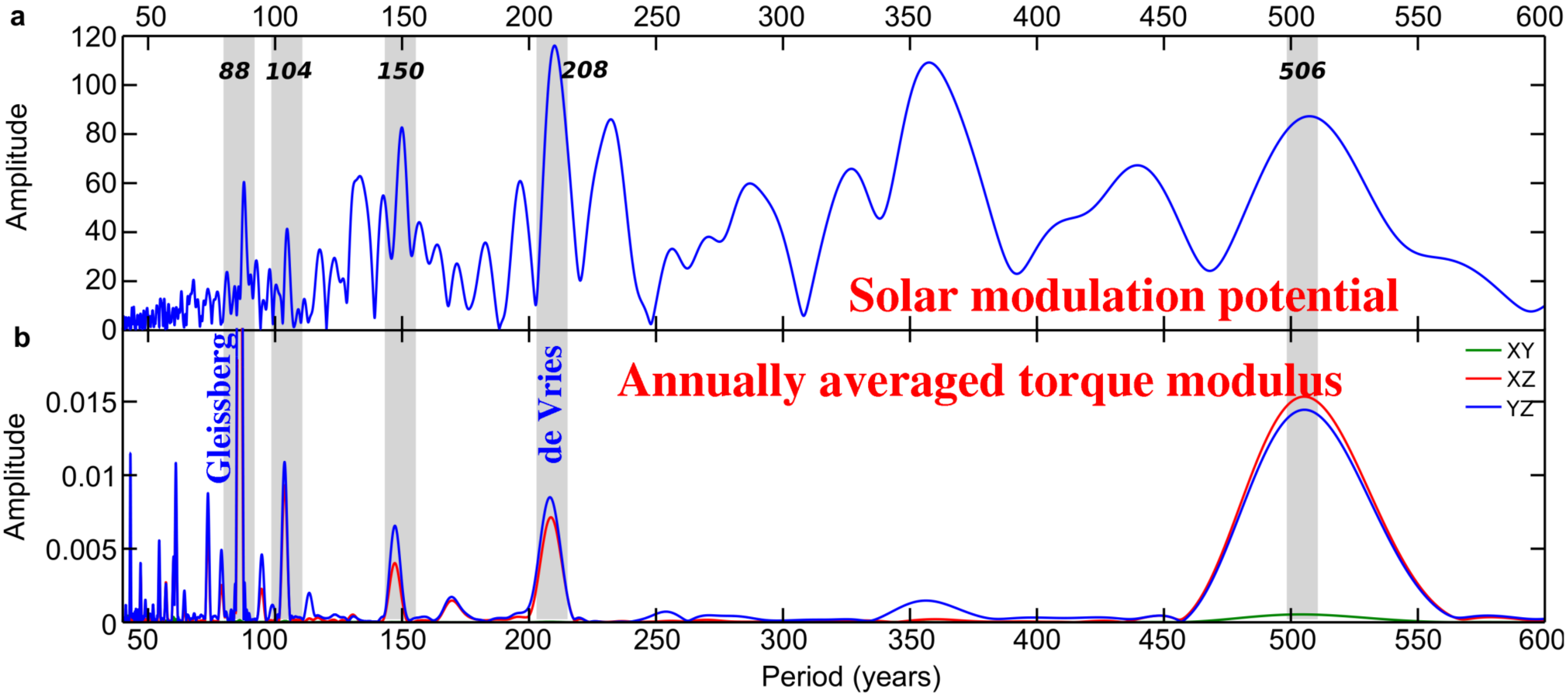


Suess-de Vries

Gleissberg

Wilson gap

Planetary motion and long periods



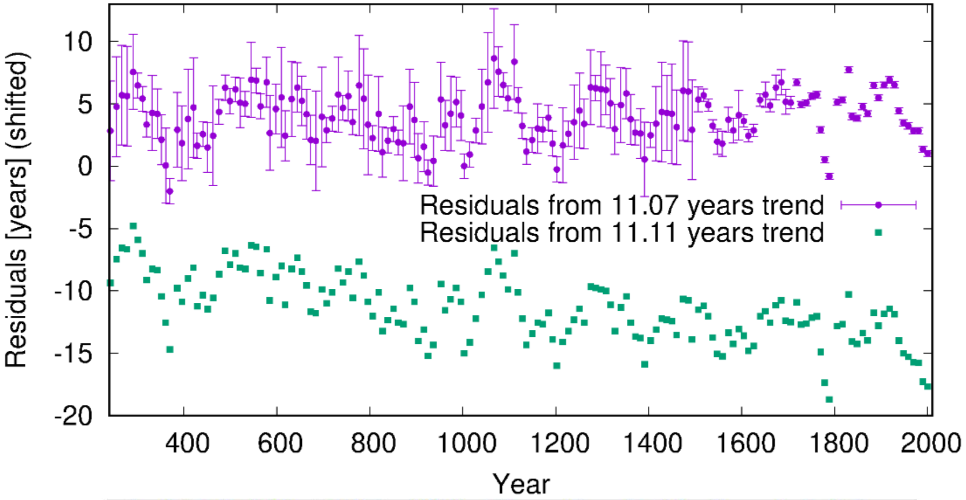
Abreu et al., Astron. & Astrophys. 548 (2012), A88

…but notice various counter-arguments by…

Cameron and Schüssler, Astron. & Astrophys. 577 (2013), A83

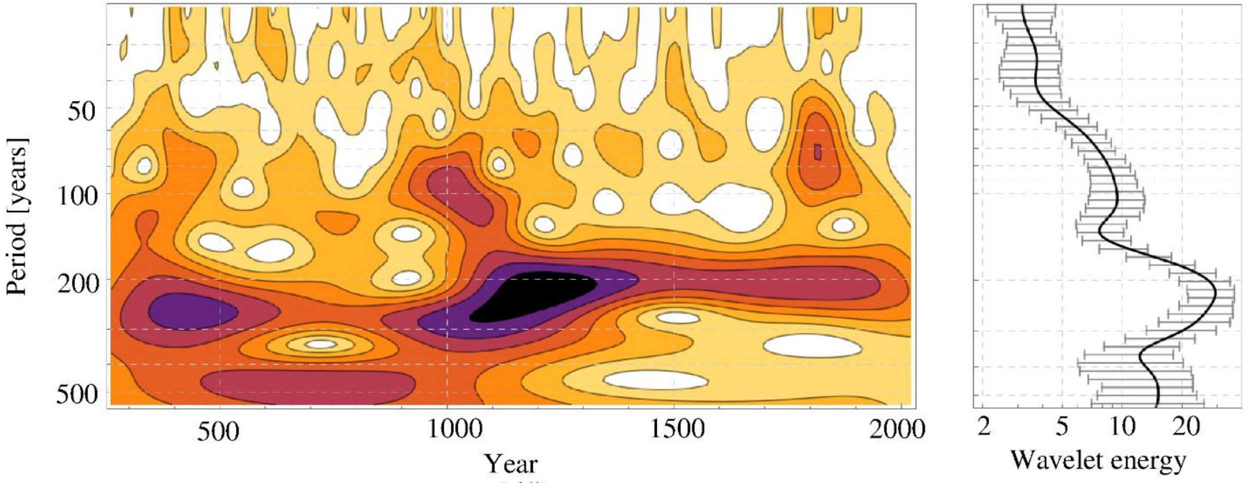
Poluianov and Usoskin, Sol. Phys. 289 (2014), 2333

Planetary motion and long periods



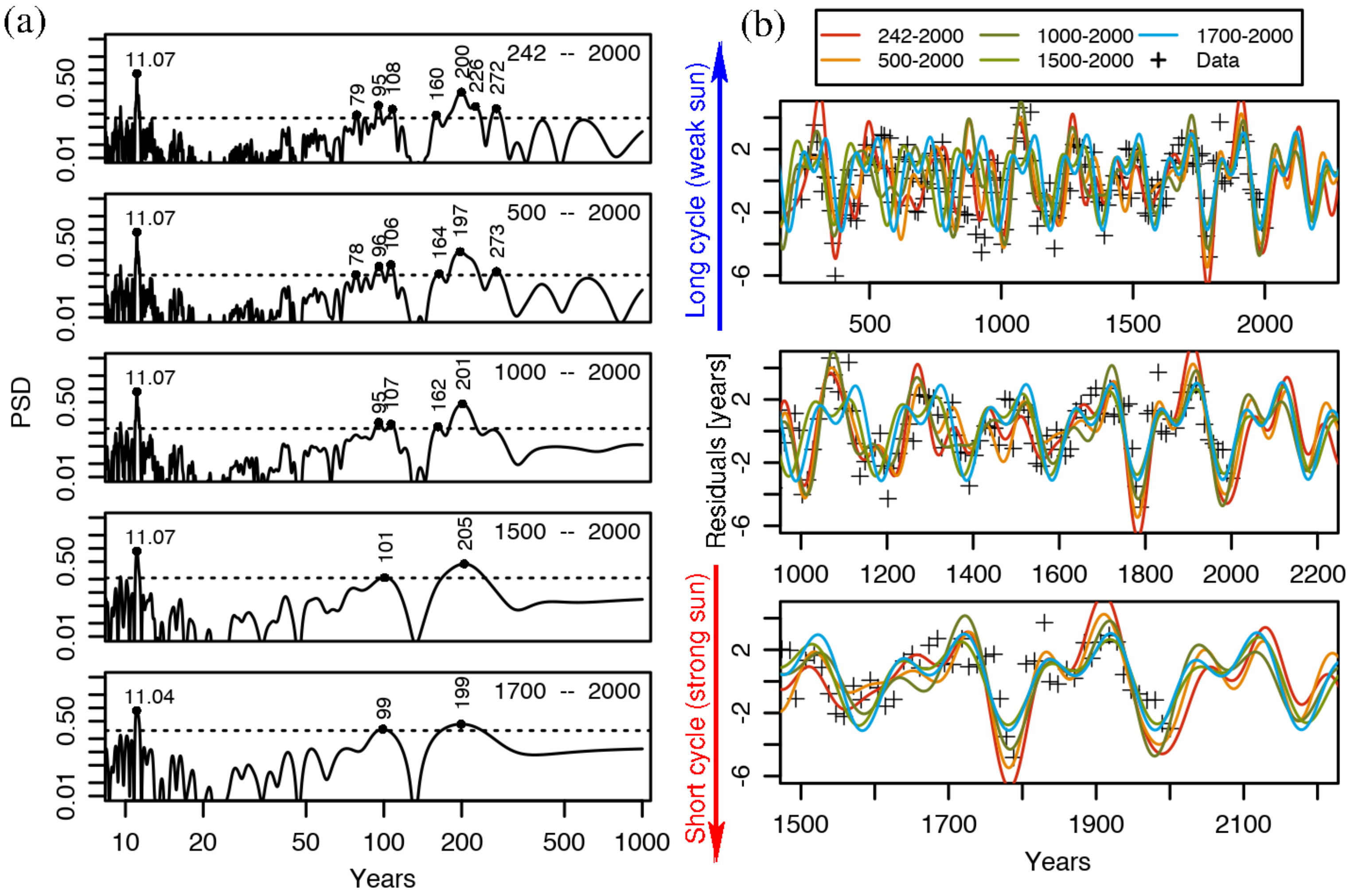
Schove´s maxima data, with two different trends subtracted…

…and wavelet analysis



Stefani et al., Magnetohydrodynamics (in press), arxiv.org/abs/1910.10383

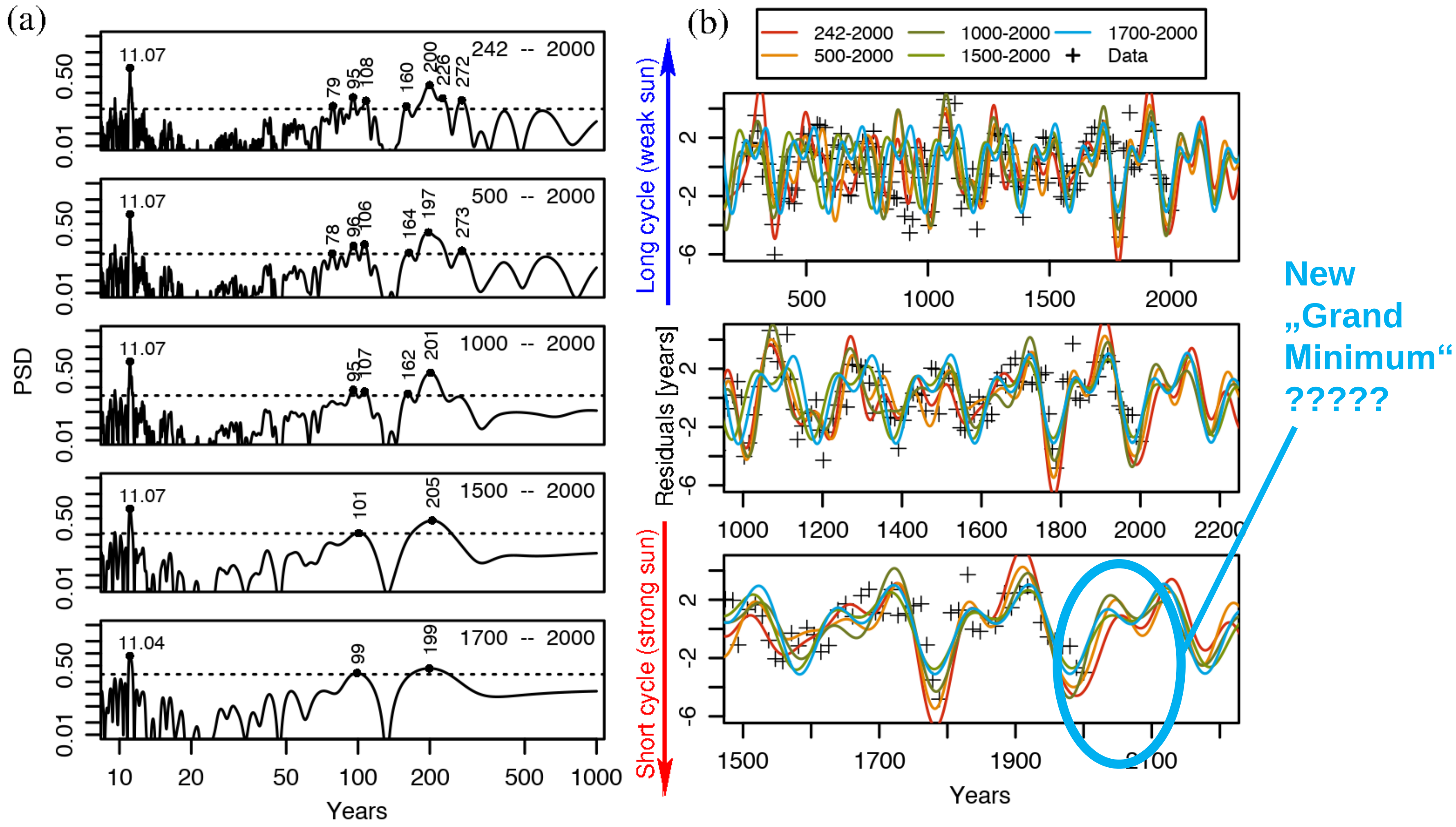
Detailed analysis with different underlying time intervals



Lomb-Scargle periodograms based an different intervals

Fits with significant harmonics

Detailed analysis with different underlying time intervals



New „Grand Minimum“ ?????

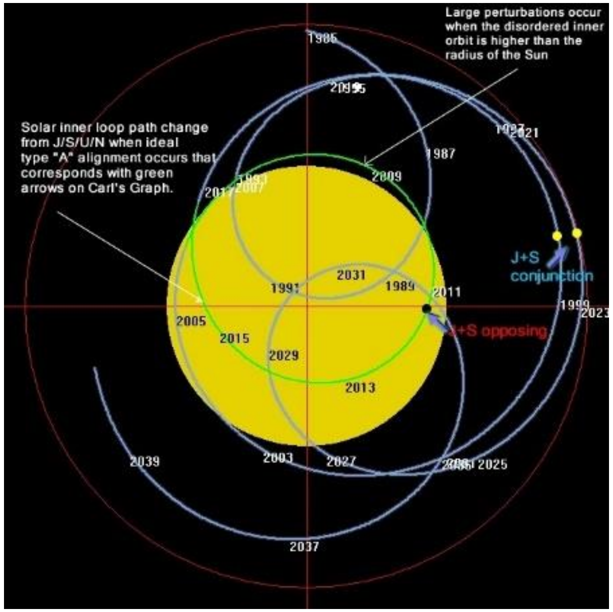
Lomb-Scargle periodograms based an different intervals

Fits with significant harmonics

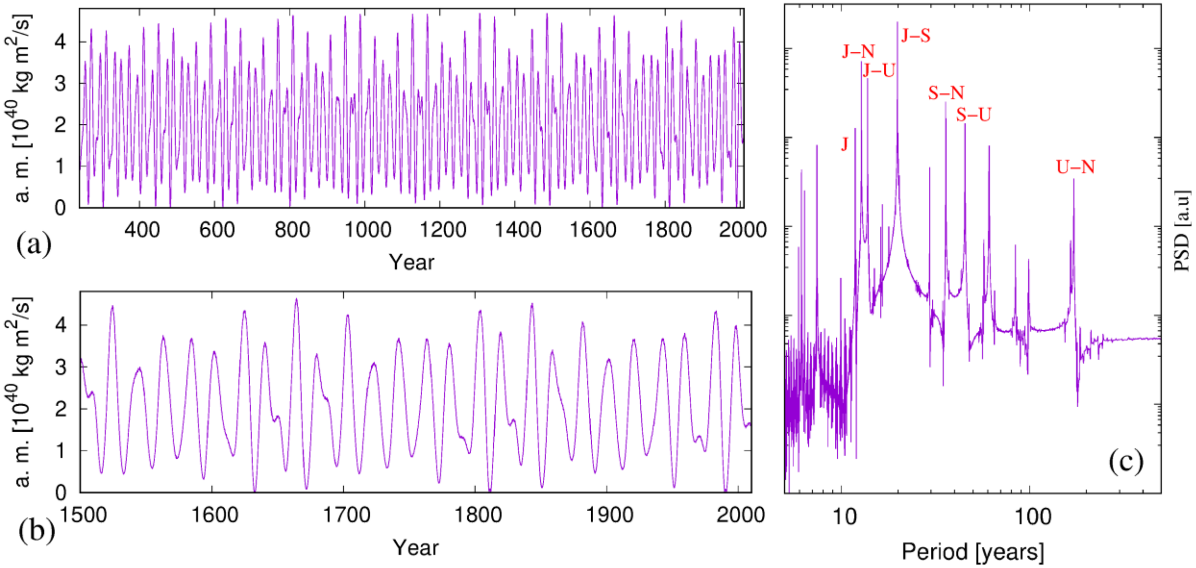
Is the Suess/de Vries cycle a beat period between 22.14 and 19.86 ?

Tidal forcing → 22.14 years
Sun around barycenter → 19.86 years
(with unclear physical
effect on the dynamo)

Beat period: 193 years
19.86 x 22.14/(22.14-19.86)



Sharp, Int J. Astron. Astrophys., vol. 3 (2013), 260



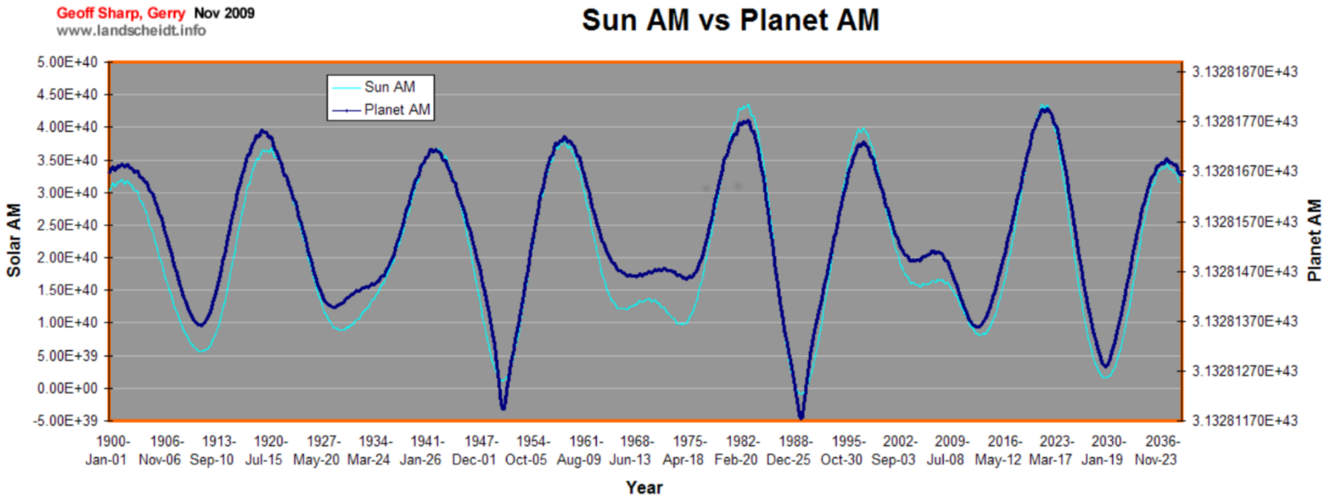
Wilson, Pattern Recogn. Phys. 1 (2013), 147; Solheim, Pattern. Recogn. Phys. 1 (2013), 159

Warning: Spin-orbit coupling is not really understood…

…despite a huge body of work…

Fairbridge, Shirley, Solar Phys. 110 (1987), 191; Charvatova, Surv. Geophys. 18 (1997), 131; Palus et al, Int. J. Bifurc. Chaos Appl. Sci. Eng. 10 (2000), 2519; Jucket, Solar Phys. 191 (2000), 201; Shirley, Mon. Not. R. Astron. Soc. 368 (2006), 280; Wolff, Patrone, Solar Phys. 266 (2010), 227; Wilson, Pattern Recogn. Phys. 1 (2013), 147; Solheim, Pattern. Recogn. Phys. 1 (2013), 159; McCracken et al., Solar Phys. 289 (2014), 3207; **Makarov et al., MNRAS 456 (2016), 665**

Interesting…



Sharp, Int J. Astron. Astrophys., vol. 3 (2013), p. 260.

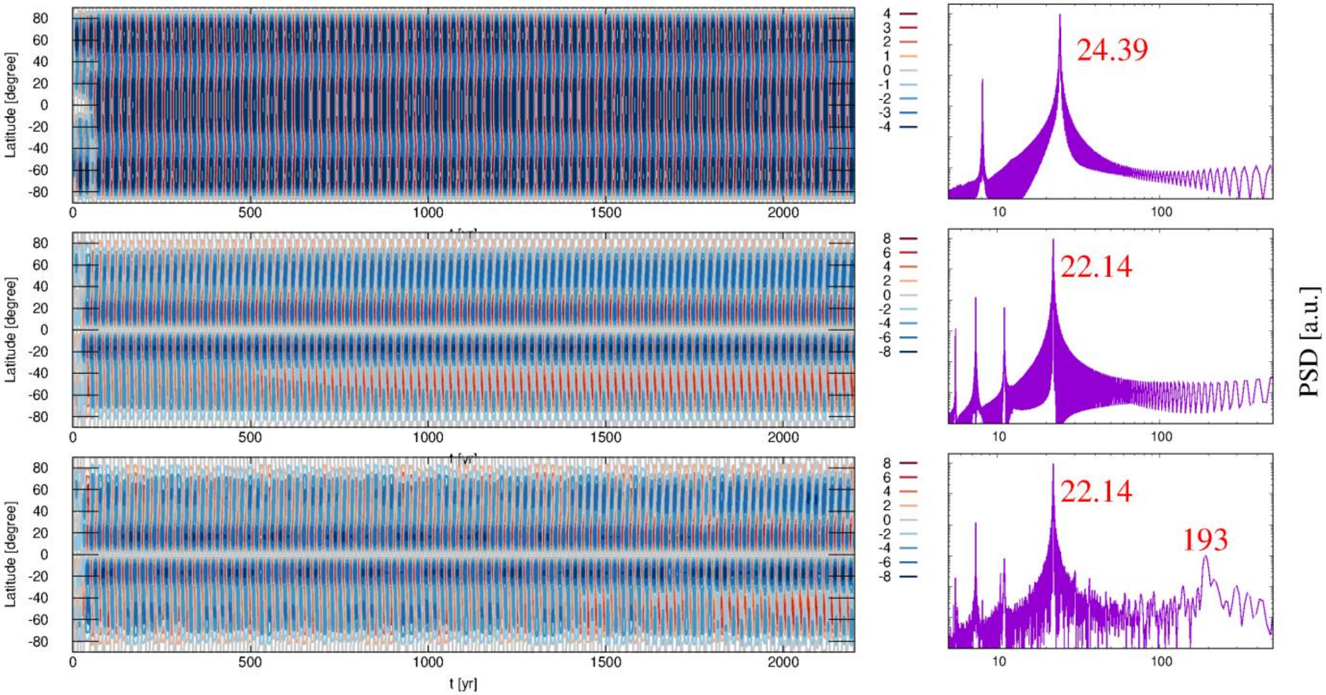
Is the Suess/de Vries cycle a beat period between 22.14 and 19.86 ?

Perhaps yes…

α–Ω-dynamo without synchronization

α–Ω-dynamo with tidal synchronization (11.07 years)

α–Ω-dynamo with tidal 11.07-years synchronization + ~19.86-year modulation



year

period

$\kappa(t) = 0.5 + 0.5\ am(t)/am_{max}$ ← Loss parameter

Stefani et al., Magnetohydrodynamics (in press),

arxiv.org/abs/1910.10383

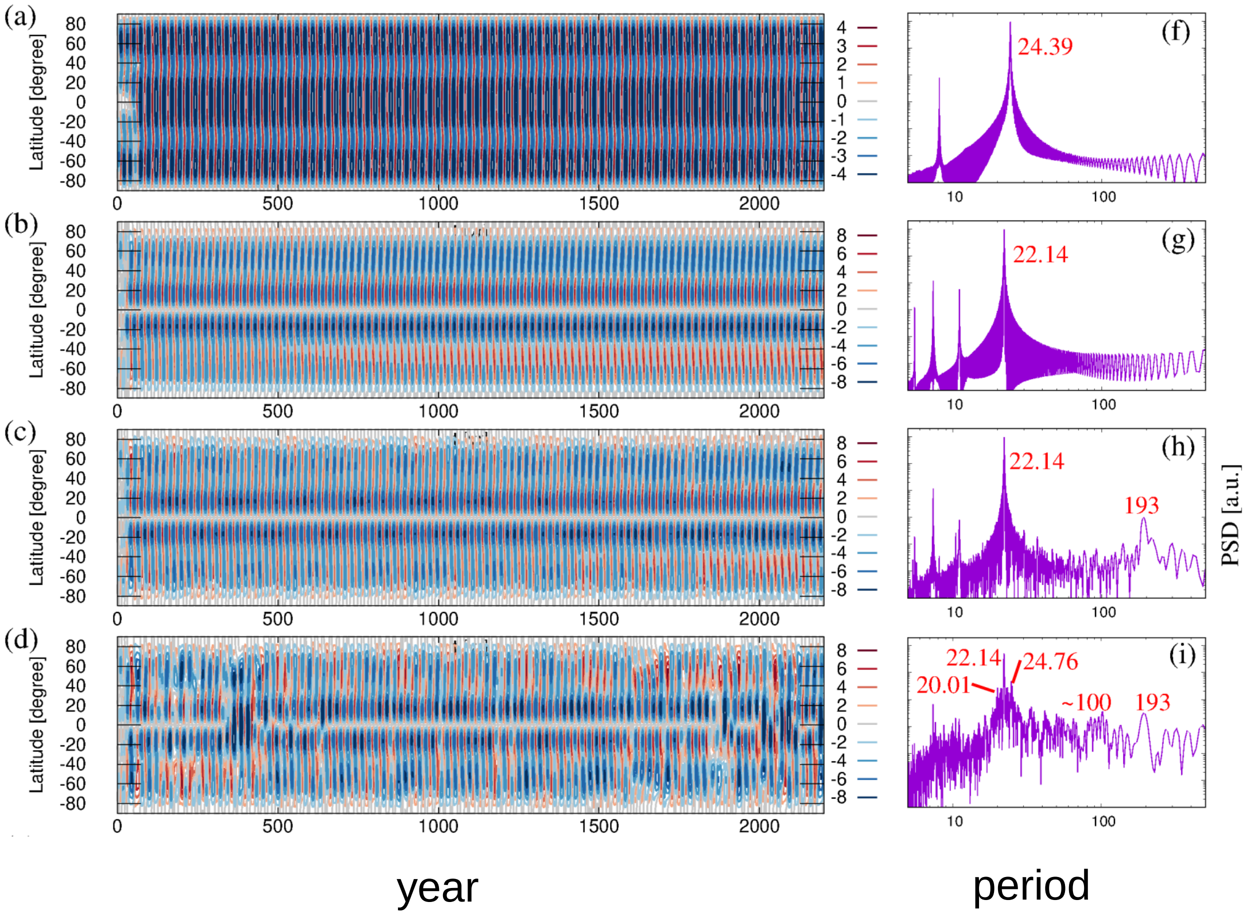
Consistent picture of Schwabe, Gleissberg, Suess/de Vries ?

α–Ω-dynamo without synchronization

α–Ω-dynamo with tidal synchronization (11.07 years)

α–Ω-dynamo with tidal 11.07-years synchronization + ~19.86-year modulation

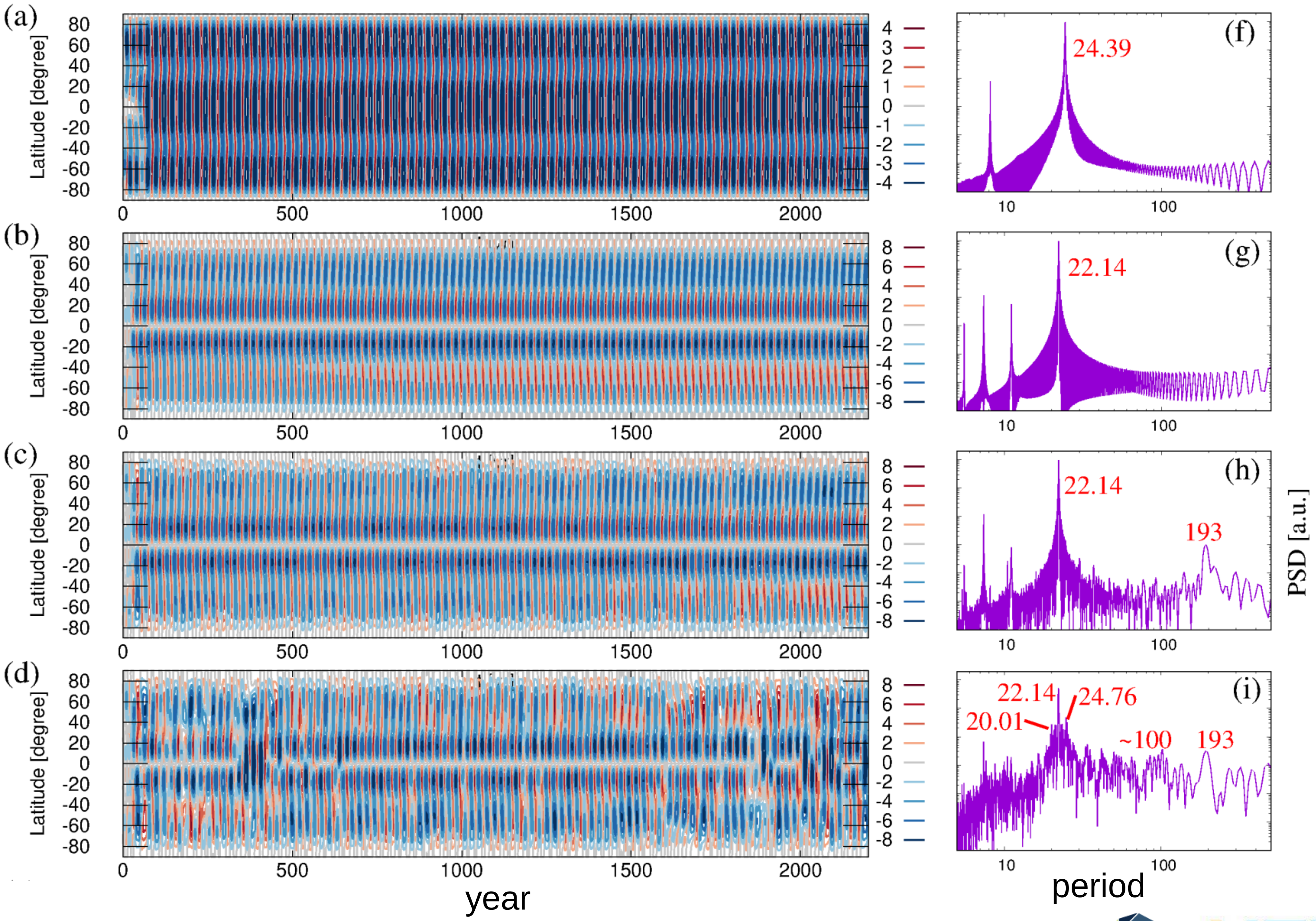
α–Ω-dynamo with tidal 11.07-years-synchronization + stronger ~19.86-year modulation



$$\kappa(t) = 0.18 + 1.0\ am(t)/am_{max}$$

Stefani et al., Magnetohydrodynamics (in press), arxiv.org/abs/1910.10383

Consistent picture of Schwabe, Gleissberg, Suess/de Vries ?



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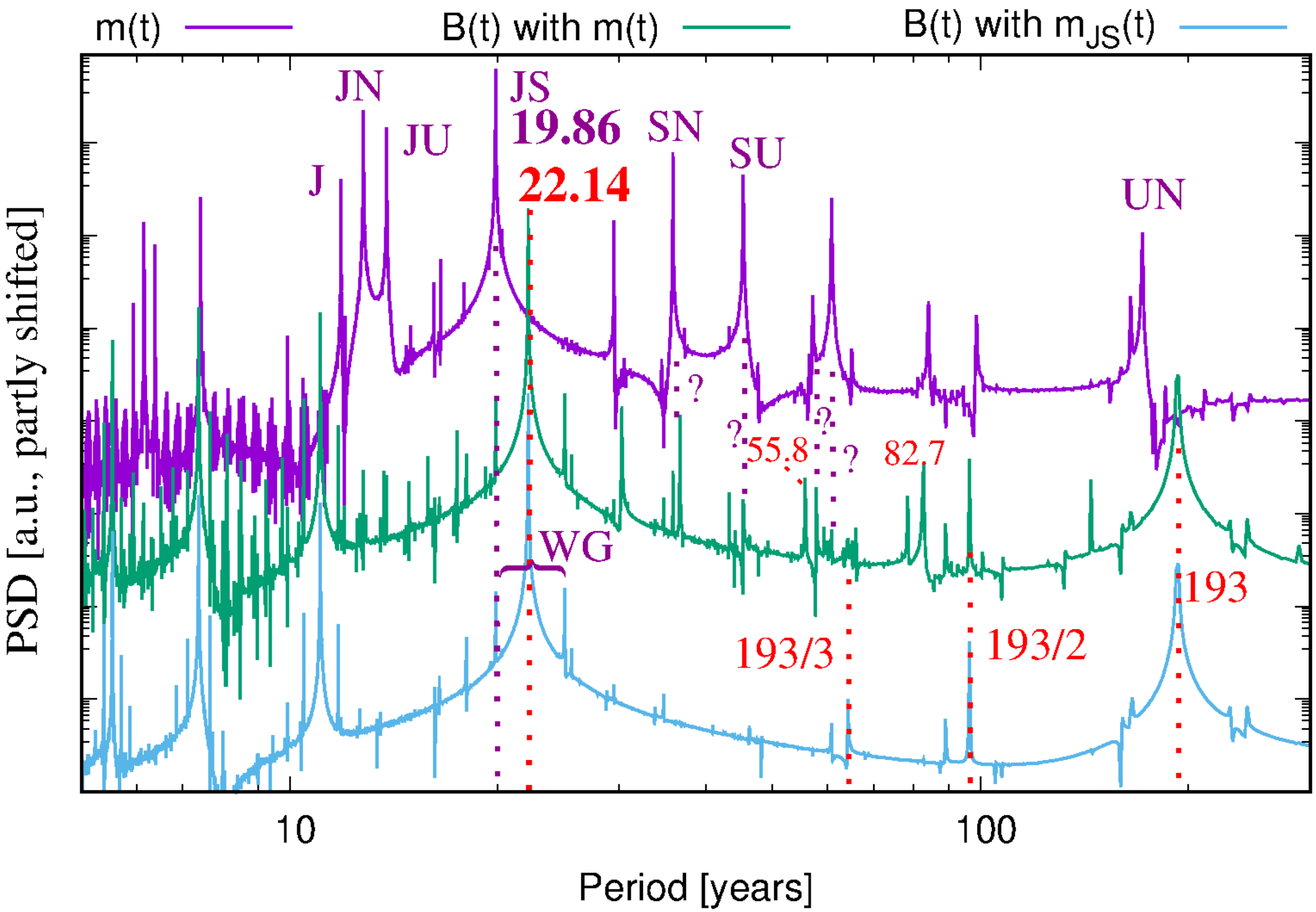
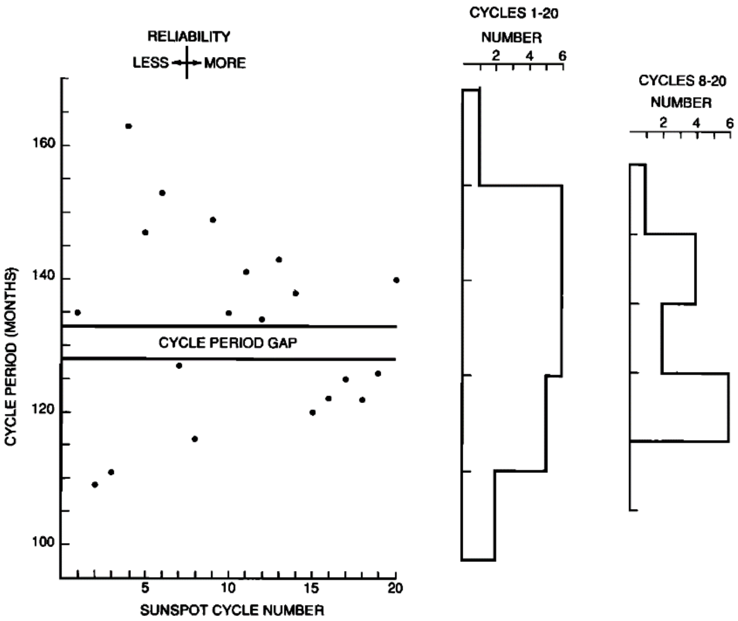
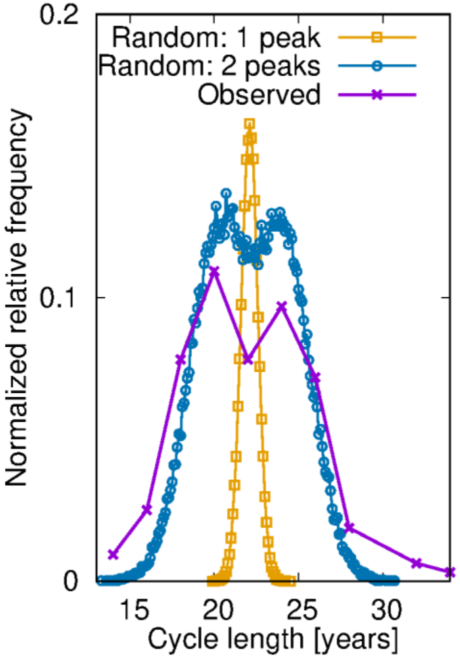
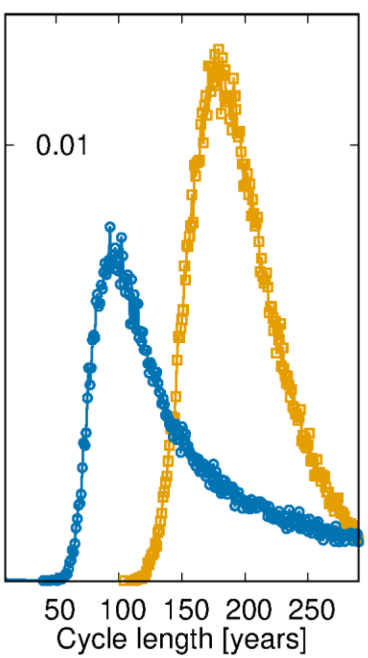


Stefani et al., Solar Physics (submitted); arxiv.org/abs/2006.08320

The Wilson gap: a consequence of synchronization+modulation?







Bimodality of cycle length fits data much better than assumption of normal distribution

Observed and 2 synthetic distributions of cycle lengths T_c

Resulting distributions of $19.86T_c/(19.86-T_c)$

Wilson, R.M.: J. Geophys. Res. 92 (1987), 10101

Summary of our model (so far)

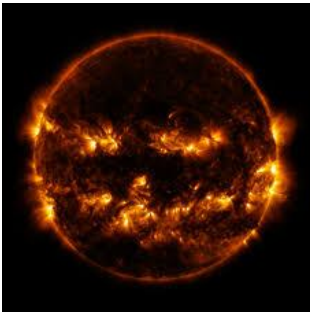
Conventional α–Ω dynamo without synchronization

11.07 years tidal forcing (m=2) synchronizes the oscillatory part of α related to some m=1 instability (Tayler instability, Rossby waves?)

Hybrid α–Ω dynamo, synchronized to 22.14 years period

Some spin-orbit coupling (poorly understood!) with dominant 19.86 years period affects field storage capacity in the tachocline (κ-parameter)

Beat period 193 years (Suess-de Vries?)



Wilson gap and second (more irregular) beat period around 100 years (Gleissberg?)

With stronger κ-variation, emergence of side bands around ~19.86 and ~24.5 years (in order to compensate the “too short” cycles)

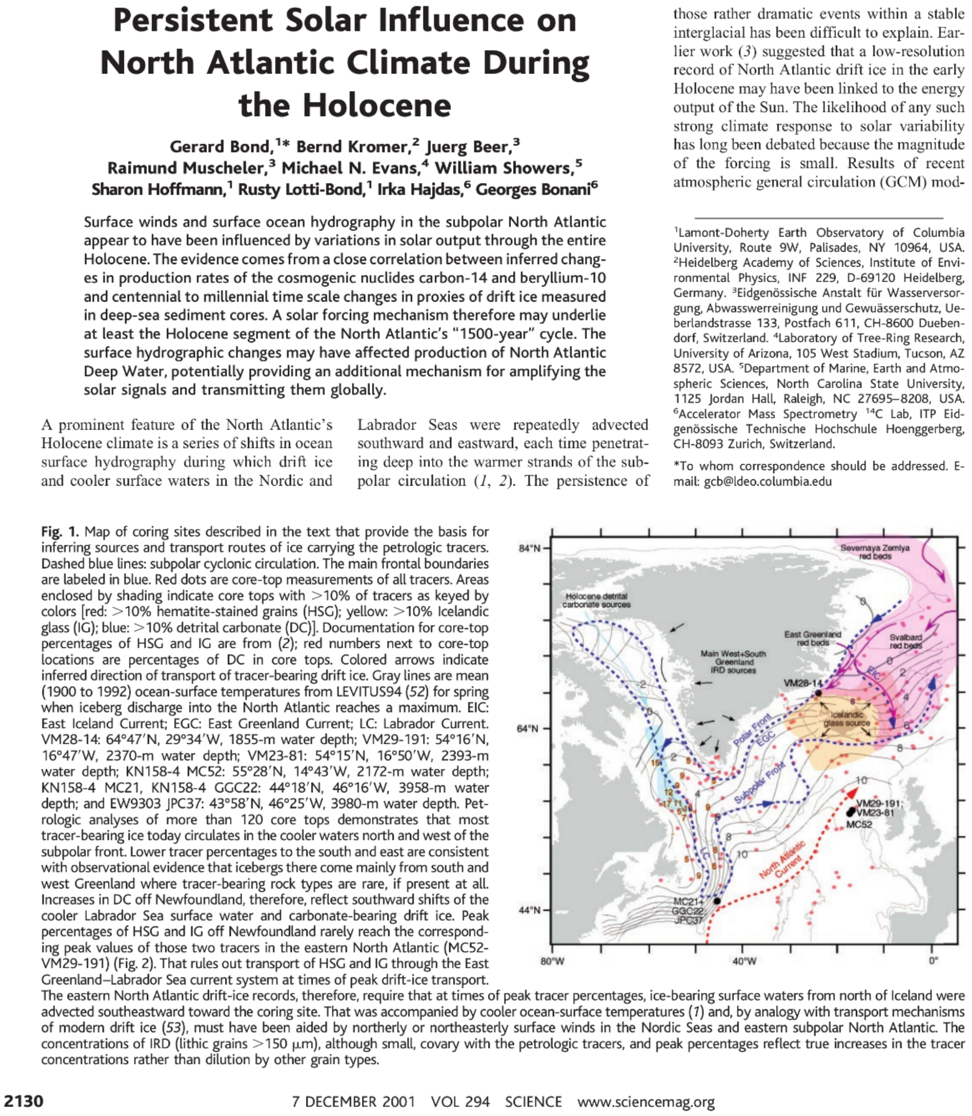
Bond

(Eddy, Hallstatt)

Bond events

Wikipedia:

Bond events are North Atlantic ice rafting events that are tentatively linked to climate fluctuations in the Holocene. Eight such events have been identified. Bond events were previously believed to exhibit a roughly c. 1,500-year cycle, but the primary period of variability is now put at ca. 1,000 years….



Persistent Solar Influence on North Atlantic Climate During the Holocene

Gerard Bond,[1]* Bernd Kromer,[2] Juerg Beer,[3]
Raimund Muscheler,[3] Michael N. Evans,[4] William Showers,[5]
Sharon Hoffmann,[1] Rusty Lotti-Bond,[1] Irka Hajdas,[6] Georges Bonani[6]

Surface winds and surface ocean hydrography in the subpolar North Atlantic appear to have been influenced by variations in solar output through the entire Holocene. The evidence comes from a close correlation between inferred changes in production rates of the cosmogenic nuclides carbon-14 and beryllium-10 and centennial to millennial time scale changes in proxies of drift ice measured in deep-sea sediment cores. A solar forcing mechanism therefore may underlie at least the Holocene segment of the North Atlantic's "1500-year" cycle. The surface hydrographic changes may have affected production of North Atlantic Deep Water, potentially providing an additional mechanism for amplifying the solar signals and transmitting them globally.

A prominent feature of the North Atlantic's Holocene climate is a series of shifts in ocean surface hydrography during which drift ice and cooler surface waters in the Nordic and Labrador Seas were repeatedly advected southward and eastward, each time penetrating deep into the warmer strands of the subpolar circulation (*1*, *2*). The persistence of those rather dramatic events within a stable interglacial has been difficult to explain. Earlier work (*3*) suggested that a low-resolution record of North Atlantic drift ice in the early Holocene may have been linked to the energy output of the Sun. The likelihood of any such strong climate response to solar variability has long been debated because the magnitude of the forcing is small. Results of recent atmospheric general circulation (GCM) mod-

Fig. 1. Map of coring sites described in the text that provide the basis for inferring sources and transport routes of ice carrying the petrologic tracers. Dashed blue lines: subpolar cyclonic circulation. The main frontal boundaries are labeled in blue. Red dots are core-top measurements of all tracers. Areas enclosed by shading indicate core tops with >10% of tracers as keyed by colors [red: >10% hematite-stained grains (HSG); yellow: >10% Icelandic glass (IG); blue: >10% detrital carbonate (DC)]. Documentation for core-top percentages of HSG and IG are from (*2*); red numbers next to core-top locations are percentages of DC in core tops. Colored arrows indicate inferred direction of transport of tracer-bearing drift ice. Gray lines are mean (1900 to 1992) ocean-surface temperatures from LEVITUS94 (*52*) for spring when iceberg discharge into the North Atlantic reaches a maximum. EIC: East Iceland Current; EGC: East Greenland Current; LC: Labrador Current. VM28-14: 64°47′N, 29°34′W, 1855-m water depth; VM29-191: 54°16′N, 16°47′W, 2370-m water depth; VM23-81: 54°15′N, 16°50′W, 2393-m water depth; KN158-4 MC52: 55°28′N, 14°43′W, 2172-m water depth; KN158-4 MC21, KN158-4 GGC22: 44°18′N, 46°16′W, 3958-m water depth; and EW9303 JPC37: 43°58′N, 46°25′W, 3980-m water depth. Petrologic analyses of more than 120 core tops demonstrates that most tracer-bearing ice today circulates in the cooler waters north and west of the subpolar front. Lower tracer percentages to the south and east are consistent with observational evidence that icebergs there come mainly from south and west Greenland where tracer-bearing rock types are rare, if present at all. Increases in DC off Newfoundland, therefore, reflect southward shifts of the cooler Labrador Sea surface water and carbonate-bearing drift ice. Peak percentages of HSG and IG off Newfoundland rarely reach the corresponding peak values of those two tracers in the eastern North Atlantic (MC52-VM29-191) (Fig. 2). That rules out transport of HSG and IG through the East Greenland–Labrador Sea current system at times of peak drift-ice transport. The eastern North Atlantic drift-ice records, therefore, require that at times of peak tracer percentages, ice-bearing surface waters from north of Iceland were advected southeastward toward the coring site. That was accompanied by cooler ocean-surface temperatures (*1*) and, by analogy with transport mechanisms of modern drift ice (*53*), must have been aided by northerly or northeasterly surface winds in the Nordic Seas and eastern subpolar North Atlantic. The concentrations of IRD (lithic grains >150 µm), although small, covary with the petrologic tracers, and peak percentages reflect true increases in the tracer concentrations rather than dilution by other grain types.

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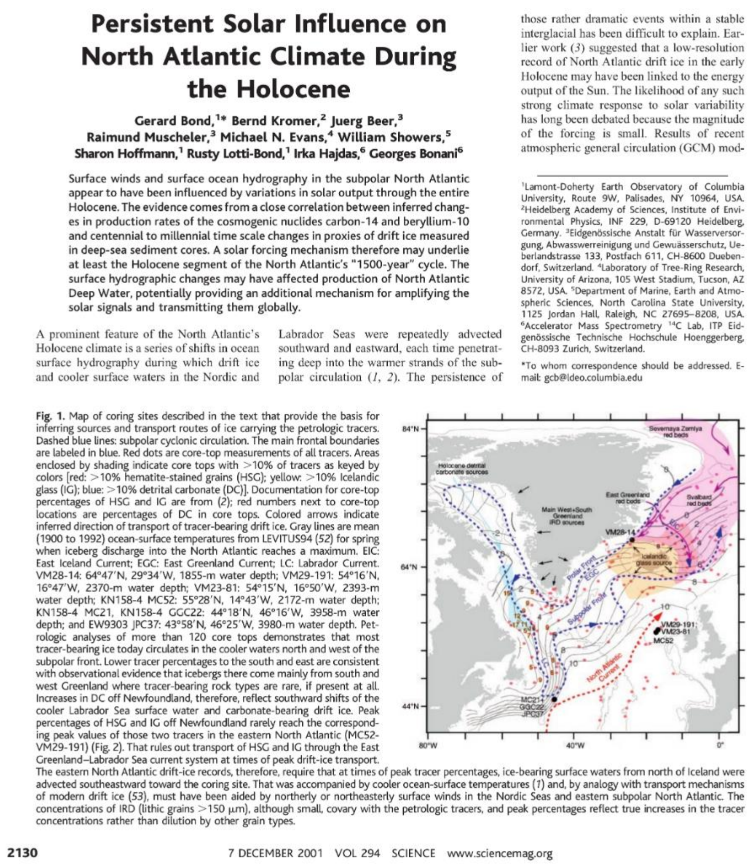
*To whom correspondence should be addressed. E-mail: gcb@ldeo.columbia.edu

2130 7 DECEMBER 2001 VOL 294 SCIENCE www.sciencemag.org

Bond, …Beer, Muscheler…et al., Science 294, 2130 (2001)

As of today, 1963 citations!

Bond events and link to the solar dynamo (^{14}C, ^{10}Be)



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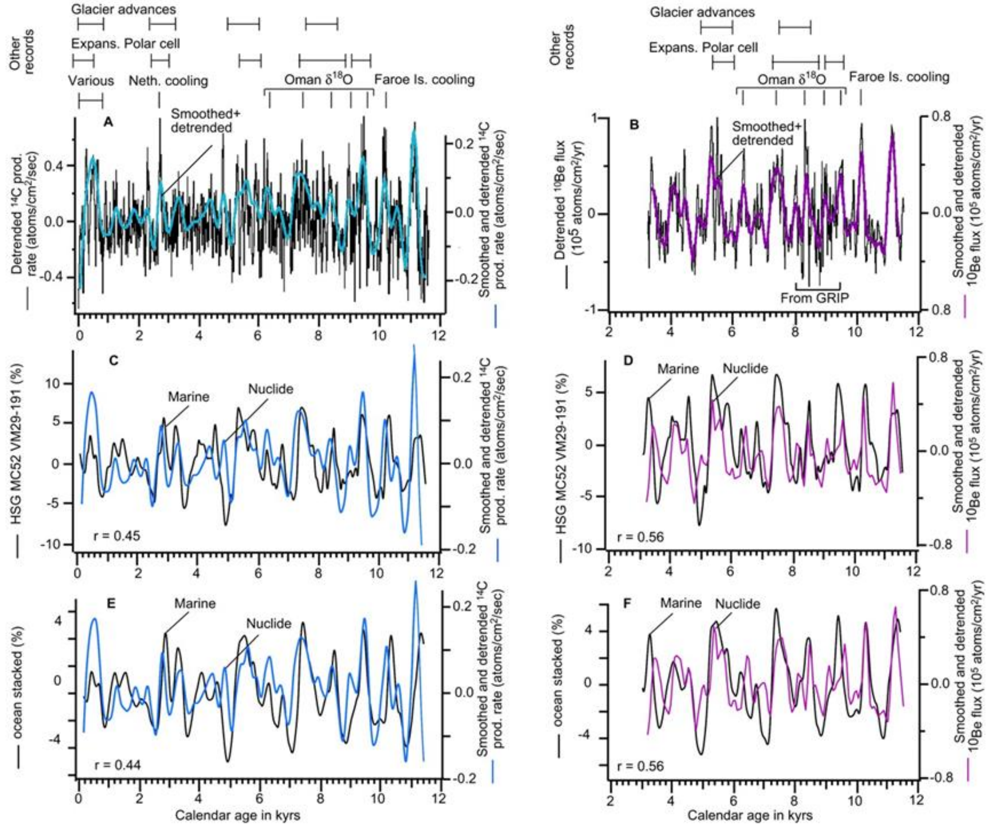
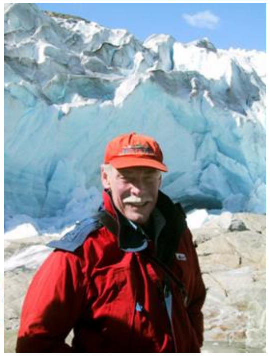


“The results of this study demonstrate that Earth's climate system is highly sensitive to extremely weak perturbations in the Sun's energy output, not just on the decadal scales that have been investigated previously, but also on the centennial to millennial time scales documented here.”

Gerard Bond, Jürg Beer et al., Science 294, 2130 (2001)



DRESDEN concept

Previous results on Schwabe, Gleissberg, Suess/de Vries

$\alpha-\Omega$-dynamo without synchronization

$\alpha-\Omega$-dynamo with tidal synchronization (11.07 years)

$\alpha-\Omega$-dynamo with tidal 11.07-years synchronization + ~19.86-year modulation

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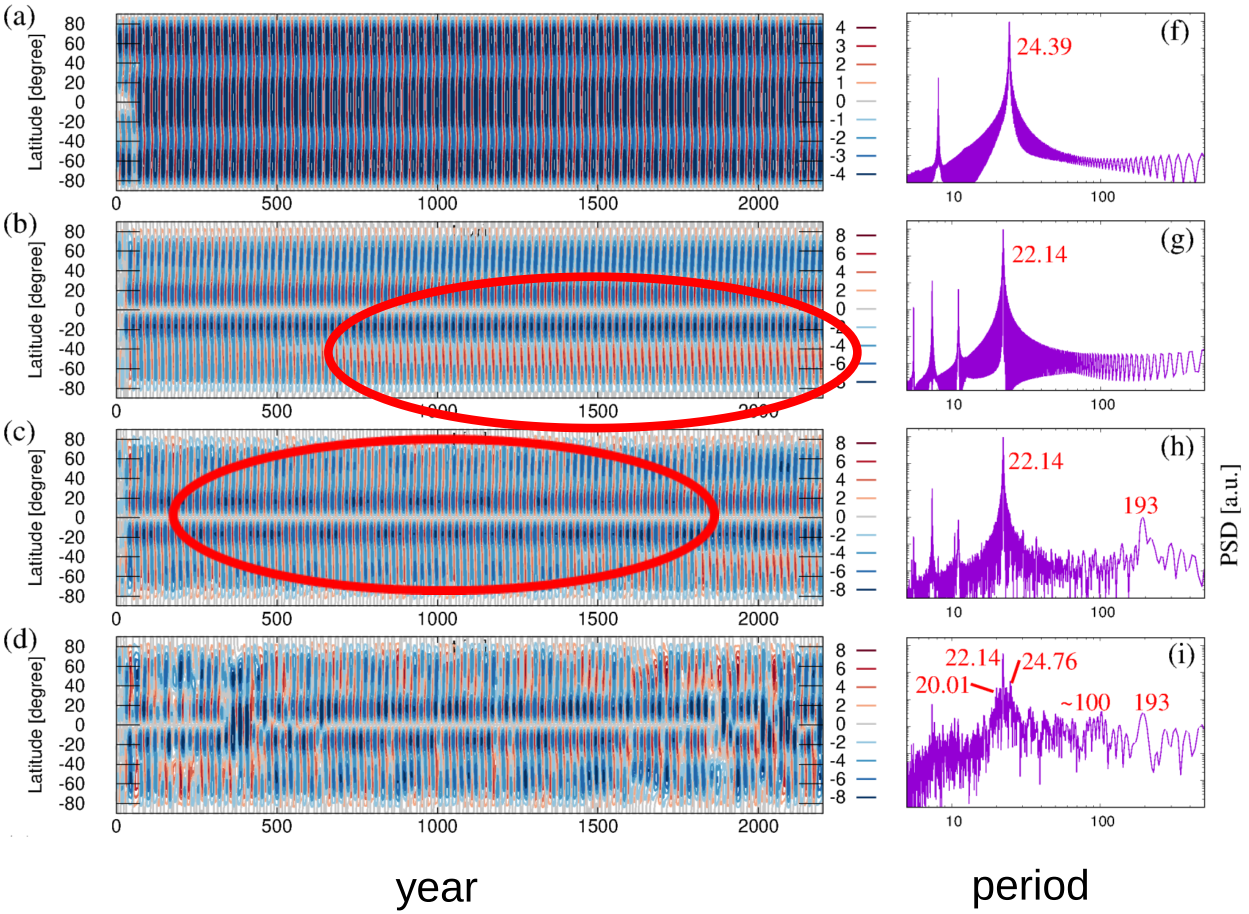

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Stefani et al., Magnetohydrodynamics (accepted), arxiv.org/abs/1910.10383

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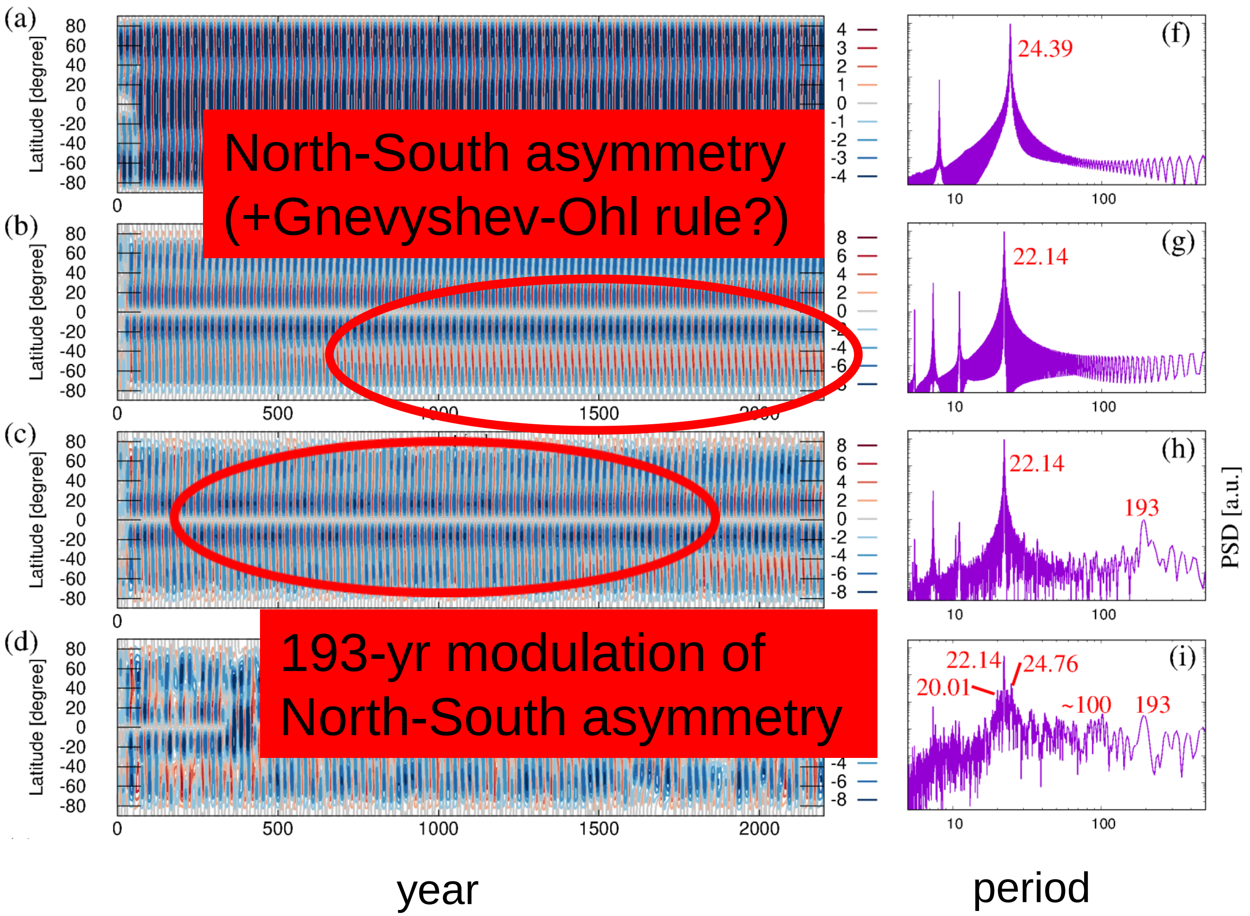

North-South asymmetry (+Gnevyshev-Ohl rule?)

193-yr modulation of North-South asymmetry

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Stefani et al., Magnetohydrodynamics (accepted), arxiv.org/abs/1910.10383

Gnevyshev-Ohl rule

The **Gnevyshev-Ohl rule** is an empirical rule according to which the sum of Wolf’s sunspot numbers over an odd cycle exceeds that of the preceding even cycle.

Gnevishev, M. N.; Ohl, A. I. (1948). "On the 22-year cycle of solar activity". Astronomical Journal (in Russian). 25 (1): 18–20.

More recently: Evidence for a 200 years modulation of the G-O- rule

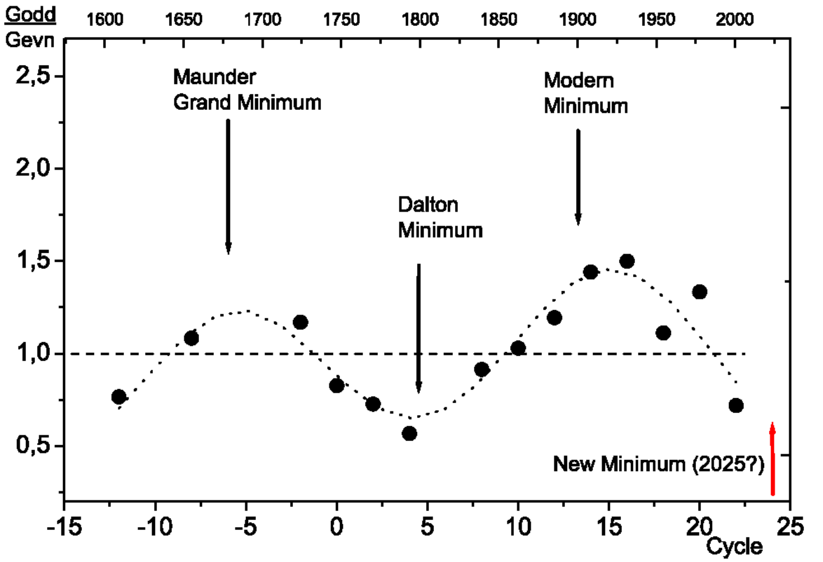

Fig. 3. The pair ratio G^{odd}_{n+1}/G^{ev}_{n}. The line $G^{odd}_{n+1}/G^{ev}_{n} = 1$ is plotted; the positions of secular minima are marked.

Tlatov, Adv. Space Res. 55, 851 (2015)

„…the secular minima of the solar activity occur in the vicinity of the extreme points of the 200-year cycles of the GO rule“…

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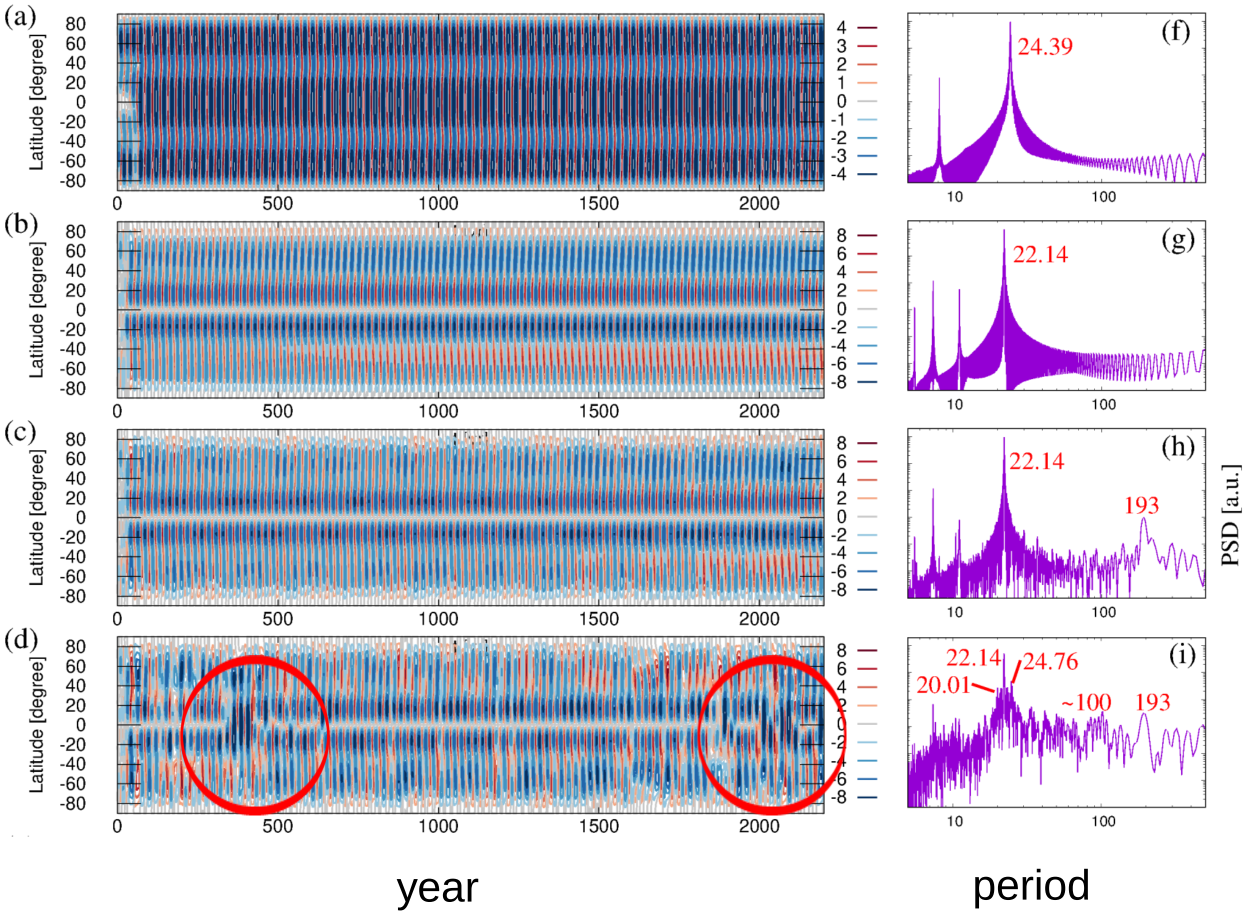

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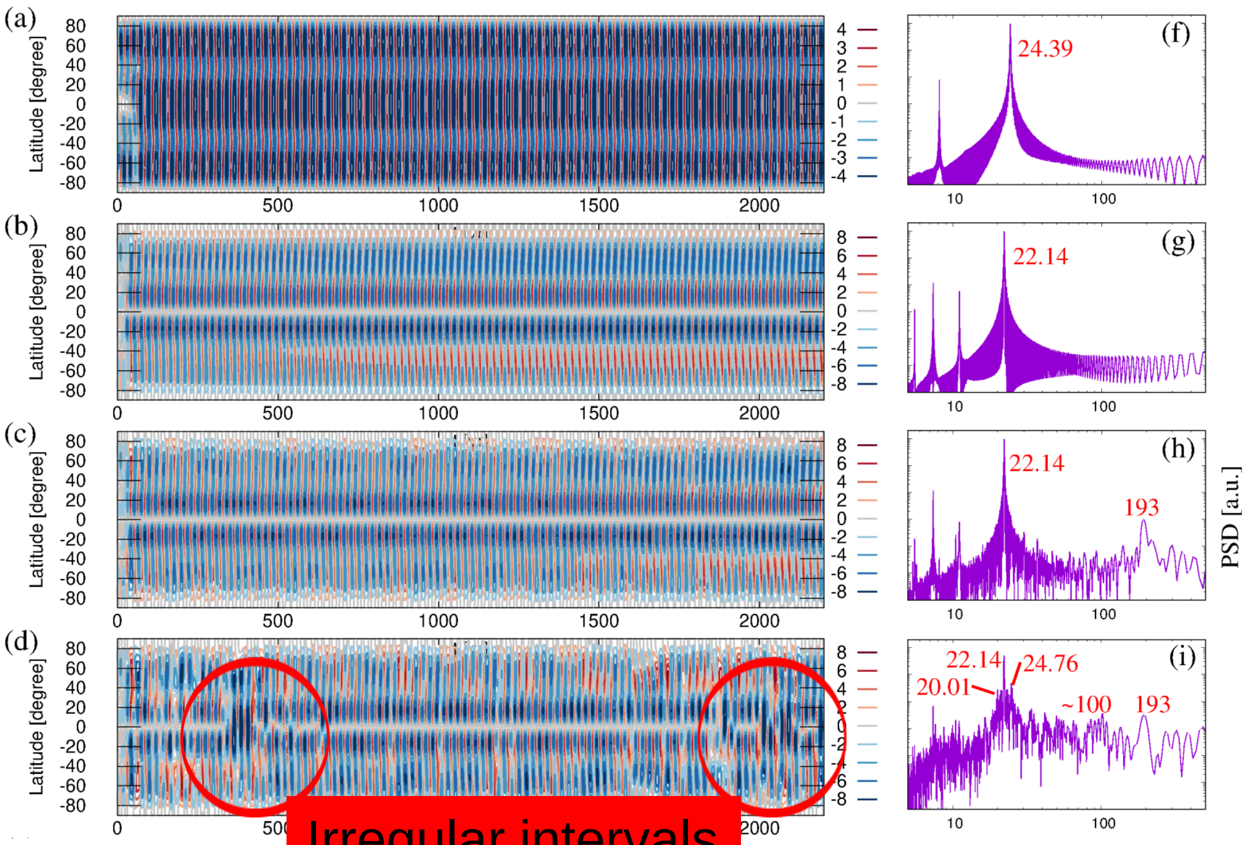


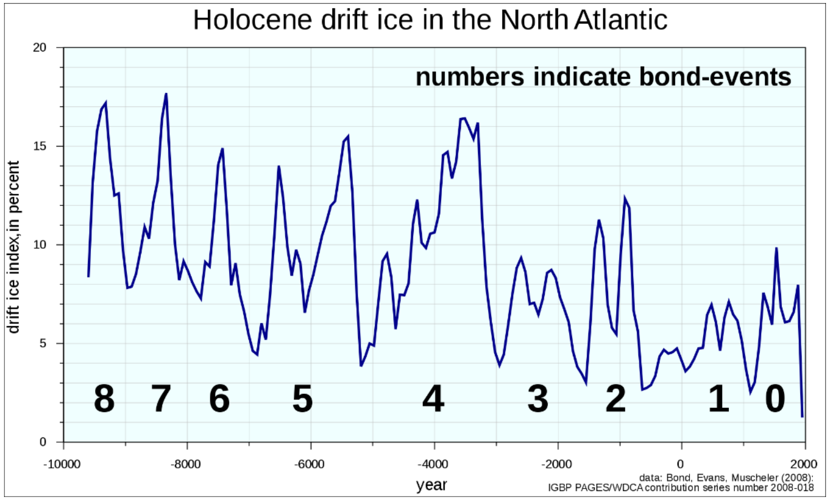
Irregular intervals (Bond events)?

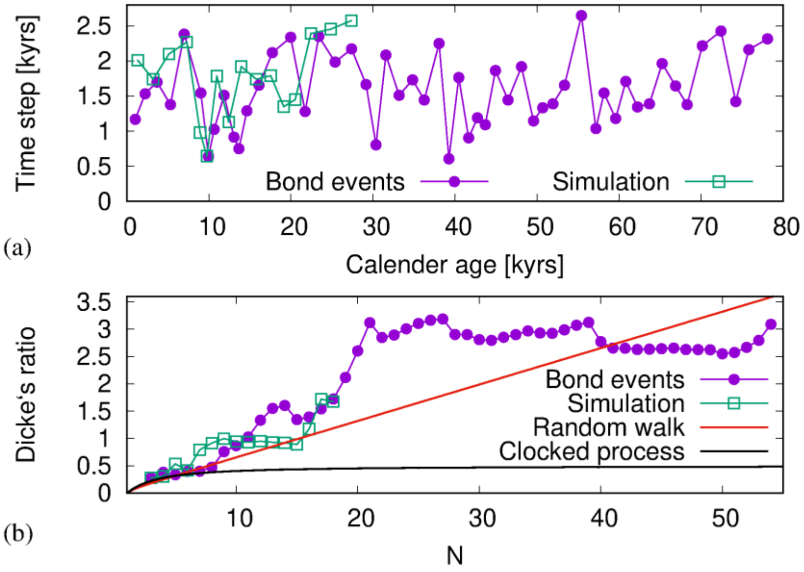
period

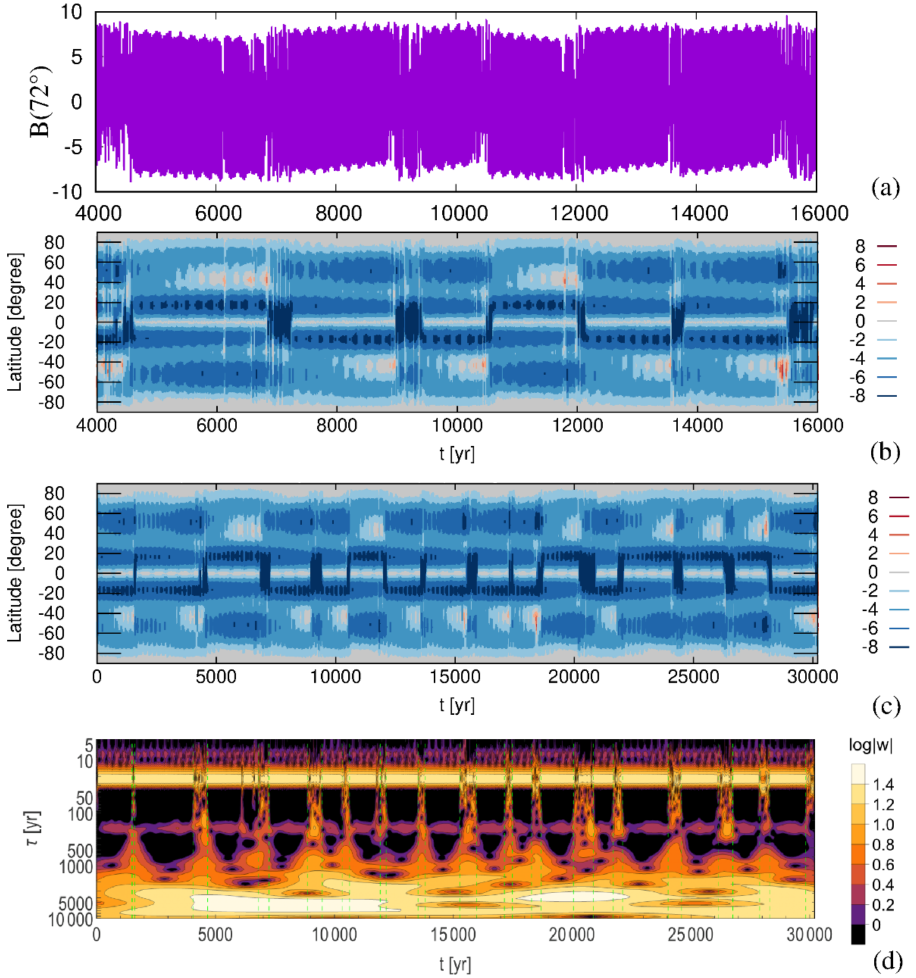
$$\kappa(t) = 0.18 + 1.0\, am(t)/am_{max}$$

Stefani et al., Magnetohydrodynamics (accepted), arxiv.org/abs/1910.10383

Bond, Eddy, Hallstatt are not cycles, but a chaotic process!







Stefani, Stepanov, Weier, Solar Physics, submitted; arXiv:2006.08320

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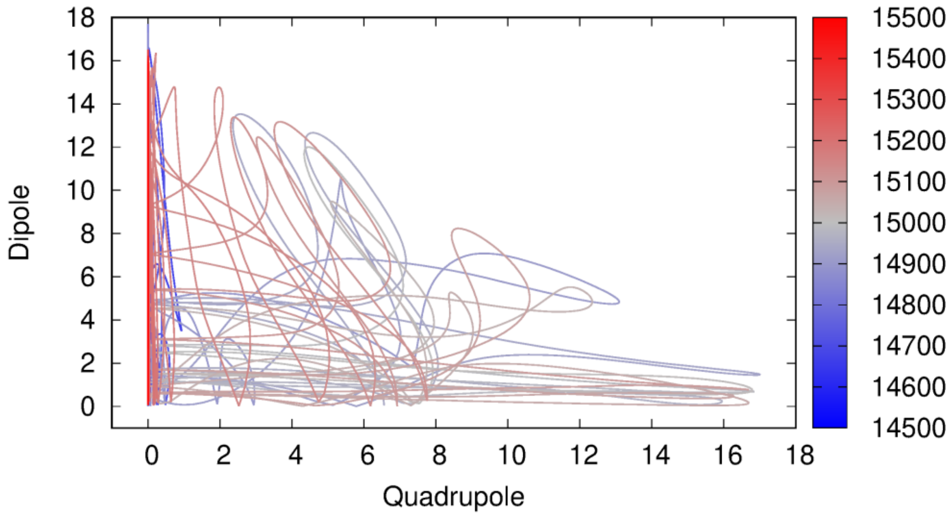
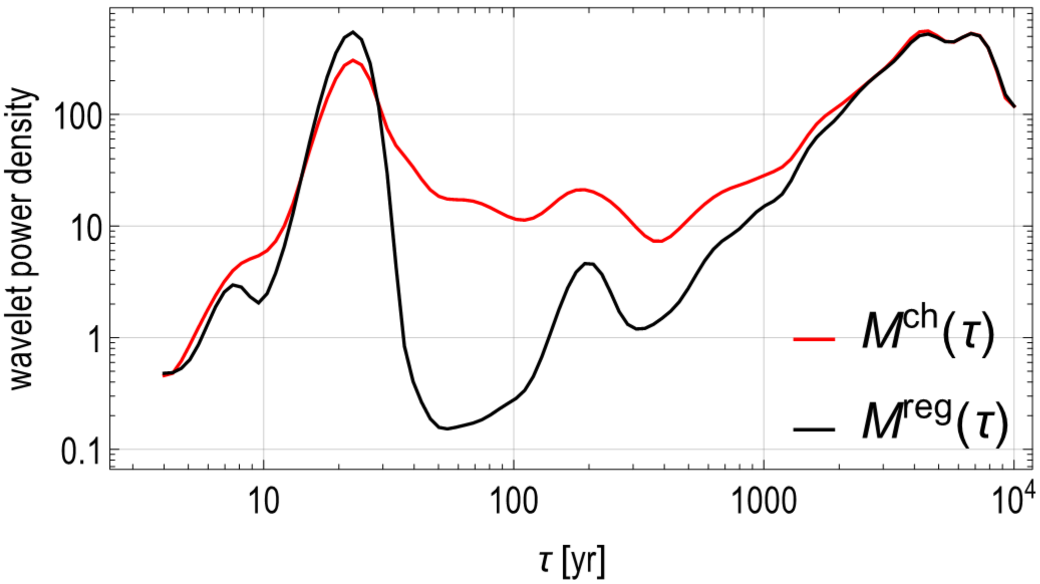


Chaotic transitions between regular and irregular intervals (supermodulation)

Weiss, N.O., Tobias, S.M: 2016, Supermodulation of the Sun’s magnetic activity: the effects of symmetry changes. Mon. Not. Roy. Astron. Soc. 456, 2654

Slightly different wavelets in regular and irregular intervals

Ma and Vaquero, 2020, New evidence of the Suess/de Vries cycle existing in historical naked-eye observations of sunspots. Open Astron. 29, 28



Summary

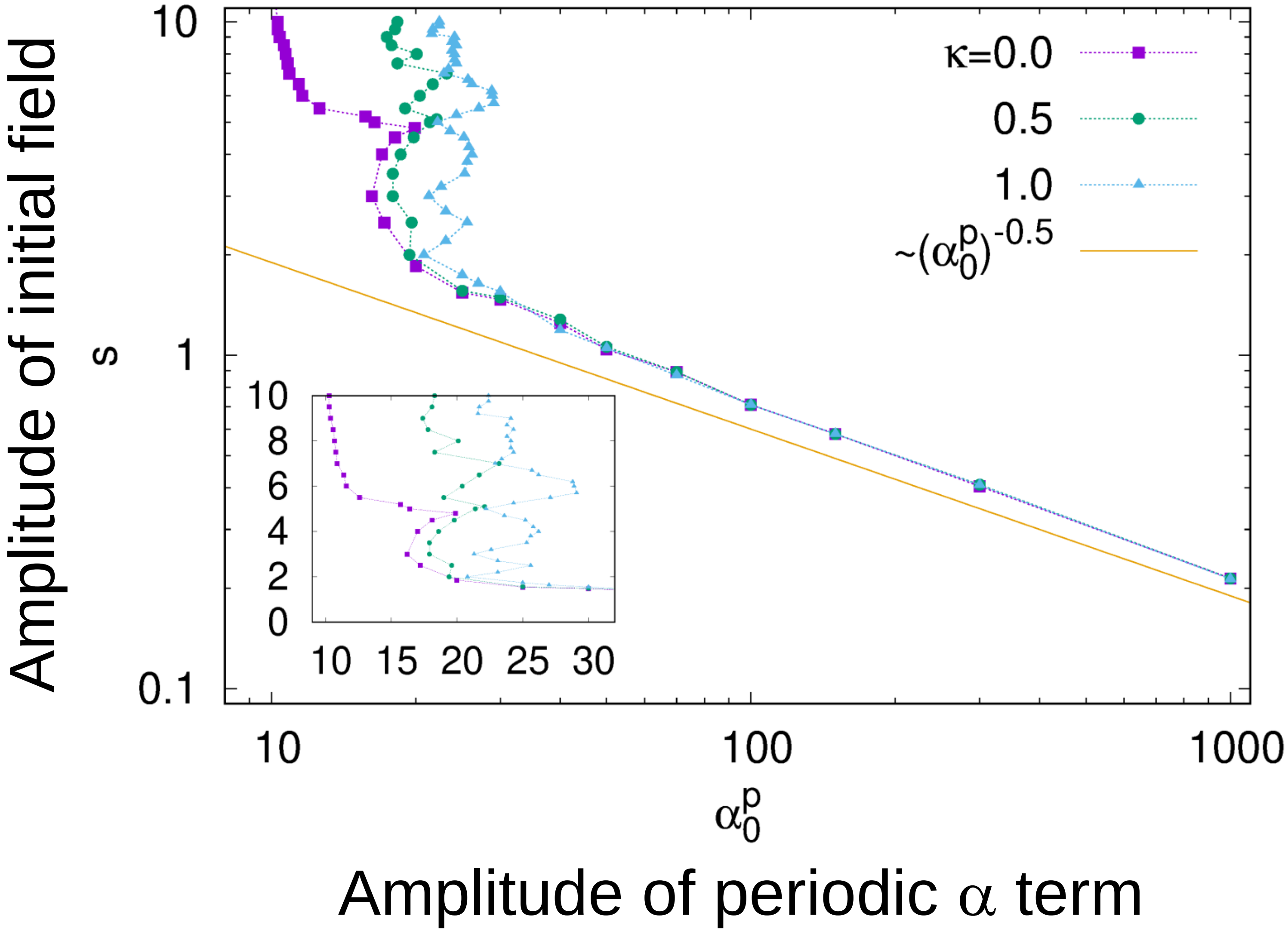
1. Our model started from a 11.07-yr tidal forcing which synchronizes (via parametric resonance) the 22.14-yr Hale cycle. The 19.86-yr cycle of angular momentum variation leads to a beat period of 193 years, which is seen in the North-South asymmetry (and the Gnevyshev-Ohl rule). If this asymmetry becomes too strong, we obtain irregular intervals, i.e. (series of) grand minima → Bond events.
2. Bond events are North Atlantic ice rafting events, linked to climate fluctuations in the Holocene, which are strongly correlated with significant ^{14}C and ^{10}B variations as proxies of solar activity. The little ice age was, very likely, the latest Bond event.
3. In the best case, we delineated a more or less **COMPLETE MODEL** of the TEMPORAL behaviour of the solar dynamo.
4. In the worst case (not to be ruled out yet) it´s **COMPLETE RUBBISH…**

Remaining problems, next steps

1. Confirmation of 11.07-yr cycle period and phase-stability in further intervals of the Holocene by radio-isotopes and algae data
2. Is 193-yr really the Suess-de Vries cycle? (Ma, Vaquero: 195-yr between 800-1340!)
3. 2D model of standard Babcock-Leighton type, but with synchronized α-component at the tachocline. Main question: How much α-oscillation is needed for synchronization (mm/s, m/s ???). Work in progress…
4. Better understanding of helicity synchronization of m=1 Tayler instability or m=1 magneto-Rossby waves (Zaqarashvili, Dikpati, Tobias…) by m=2 tidal forcing.
5. Better understanding of spin-orbit coupling urgently needed!
6. What about m=0 instabilities (Super-HMRI, Mamatsashvili 2019) and their sensitivity to any m=2 forcing?

Thank you for your attention

A pure Tayler-Spruit dynamo with periodic α forcing (it works!)



Stefani et al., Solar Physics 294 (2019), 60