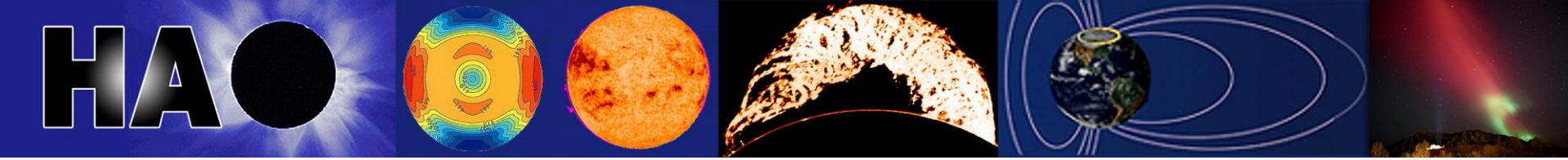
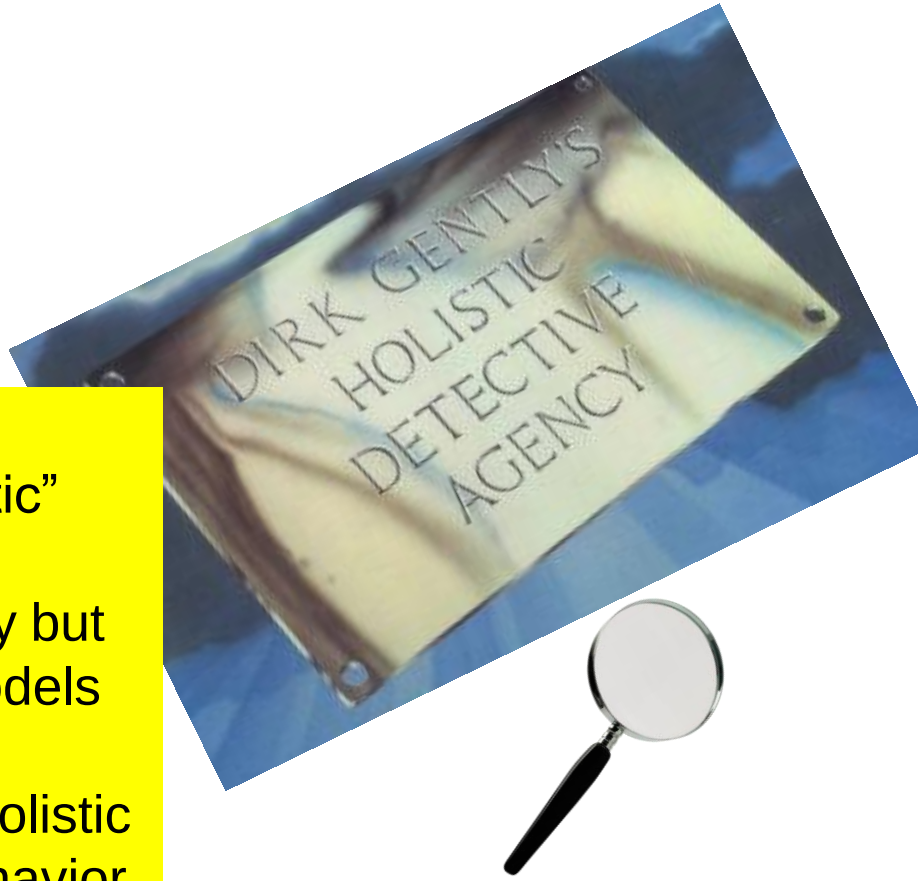


"Heinrich Schwabe's holistic detective agency"

Philip Judge, Ricky Egeland*

High Altitude Observatory, NCAR



1. Sun alone is a complex system, emergence, total is > Σ of parts=> "holistic"

2. The Sun alone has provided necessary but not sufficient data to choose dynamo models

3. The Sun is one of many realizations, holistic approach demands stellar ensemble behavior

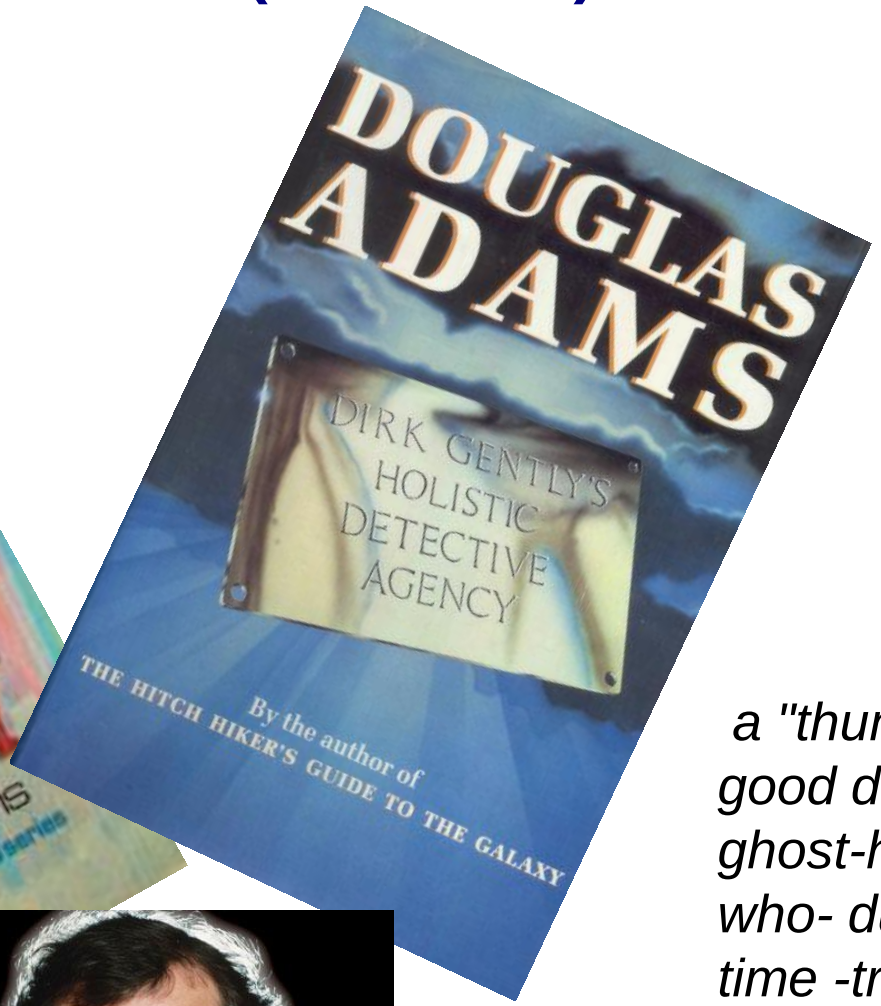
*Also Montana State University

The National Center for Atmospheric Research is sponsored by the National Science Foundation.

NCAR

NSF

Douglas Adams (1952-2001)



a "thumping good detective-ghost-horror-who- dunnit-time -travel-romantic-musical-comedy-epic"

Heinrich Schwabe (1789-1875)

Jahr.	Gruppen.	Fleckenfreie Tage.	Beobachtungs-Tage.
1826	118	22	277
1827	161	2	273
1828	225	0	282
1829	199	0	244
1830	190	1	217
1831	149	3	239
1832	84	49	270
1833	33	139	267
1834	51	120	273
1835	173	18	244
1836	272	0	200
1837	333	0	168
1838	282	0	202
1839	162	0	205
1840	152	3	263
1841	102	15	283
1842	68	64	307
1843	34	149	312
1844	52	111	321
1845	114	29	332
1846	157	1	314
1847	257	0	276
1848	330	0	278
1849	238	0	285
1850	186	2	308

Here we contend that Schwabe's work began a detective story that is also something of a

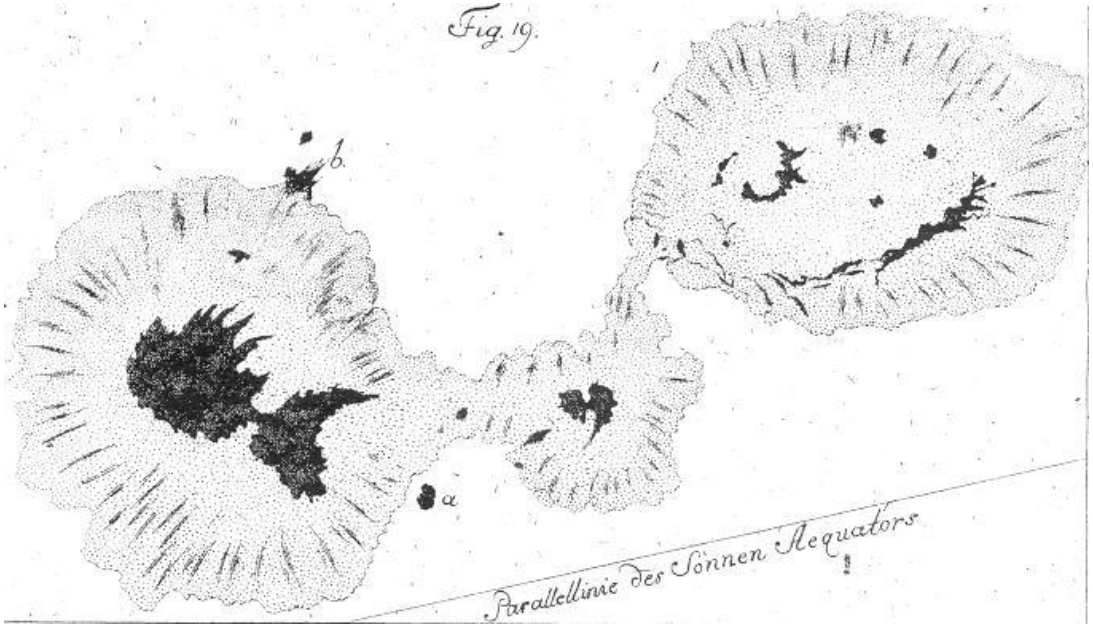
"ghost-horror-who-dunnit-time travel-musical-comedy-epic".

Summary

- Driving science questions
- The Sun in isolation
- The Sun as a star
- Conclusions

Driving science questions. Why is the Sun obliged to

- 1. regenerate its global magnetic field every 22 years given:
  - 10^5 yr Kelvin-Helmholtz timescale?
  - $10^{8\text{-}9}$ yr magnetic diffusion ($R_\odot^2/\eta$) timescale?
- form such a thing as a 2. sunspot or a 3. corona?
- 4. produce flares, CMEs?



Sunspot drawing by Johann Hieronymus Schroeter (1745-1816)

Why do physicists care? The Sun from first principles:

$\tau_{KH}=10^5$ yr, but

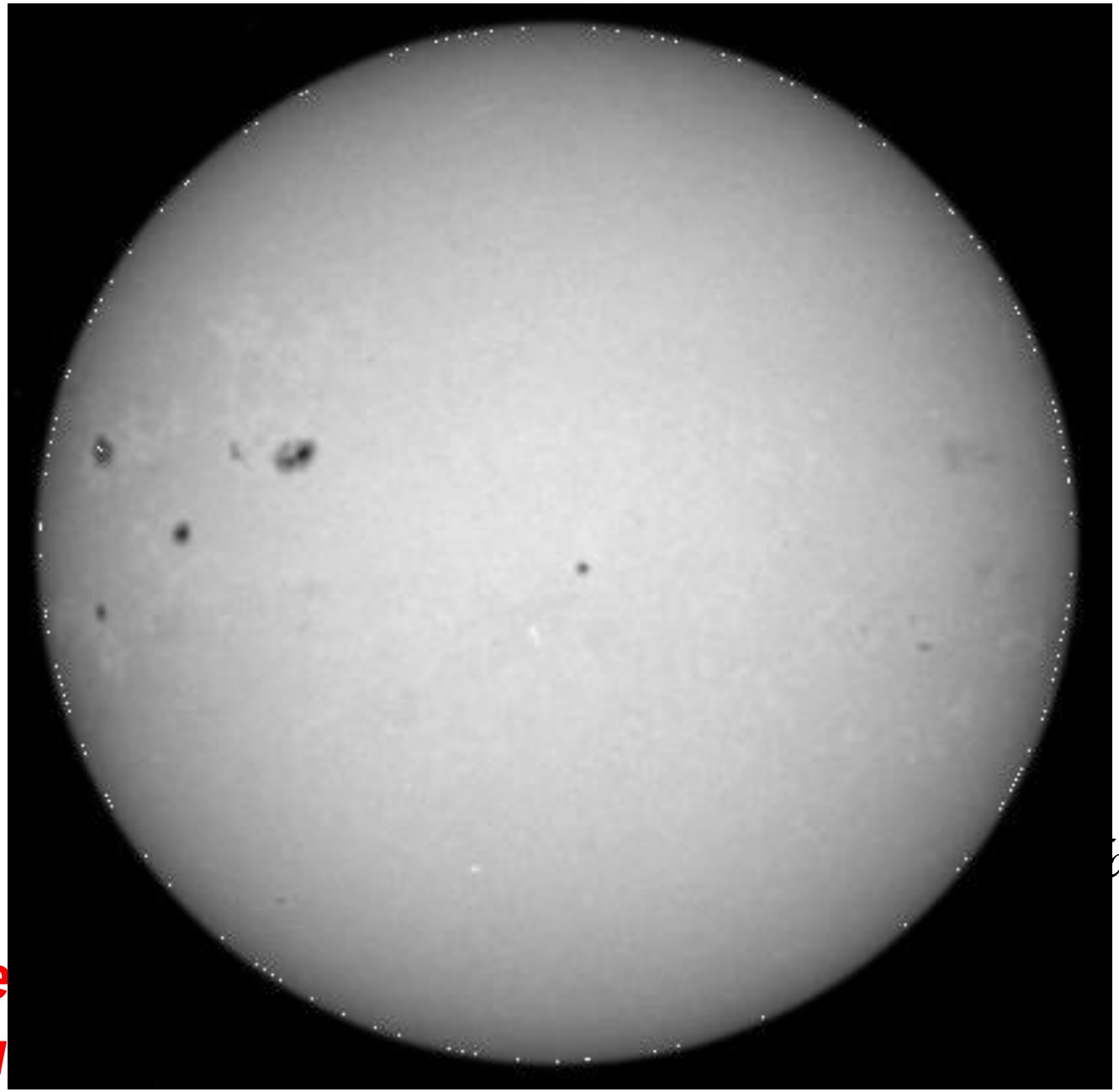
$$\frac{\partial \mathbf{B}}{\partial t} =$$ non-linear

= ??

Yet-
11 year cycle
The Sun is a global magnetic machine that

- generates order from chaos
- generates high frequencies
- generates high energy phenomena

"Emergence"
a property of a complex system



ar

He

bu

Summary

- Driving science questions
- The Sun in isolation
- The Sun as a star
- Conclusions

Studying the global solar dynamo in isolation

FACTS (observed)

Surface:

- 11 year sunspot cycle
- 22 year magnetic cycle
- modest tilts (Joy's law)
- preferred lat/long
- spots highly concentrated
- migration to poles (diffuse) & equator (spots)

INFERENCES

?

- surface poloidal field
- spots = toroidal field

>few 10^4 G from deep interior

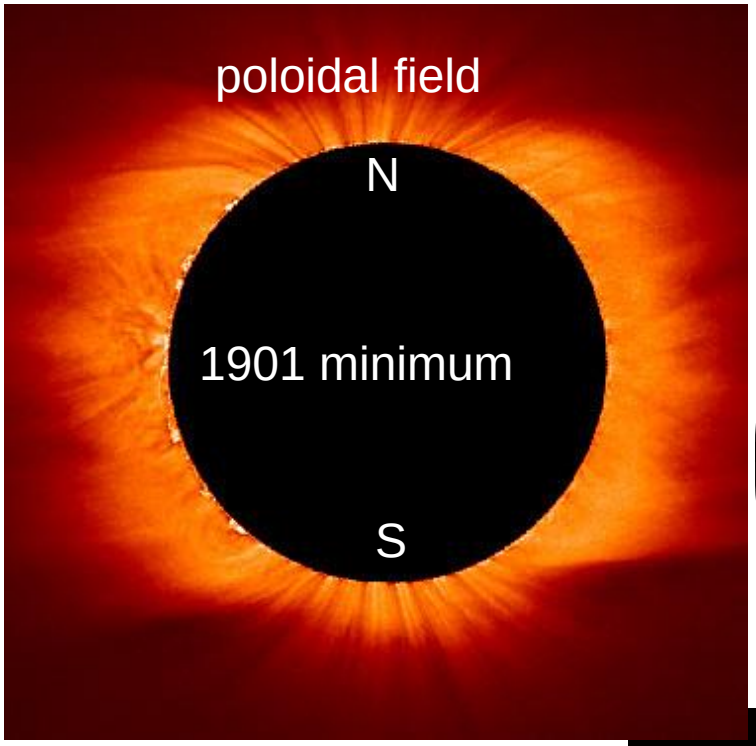
- dynamo waves.., ?

Interior:

- Unanticipated rotation profile (first T. Brown & Morrow 1987)

- differential rotation creates toroidal field (Ω-effect), $\omega(r,\theta)$

Large-scale surface solar magnetism



eclipses- “lines of force”

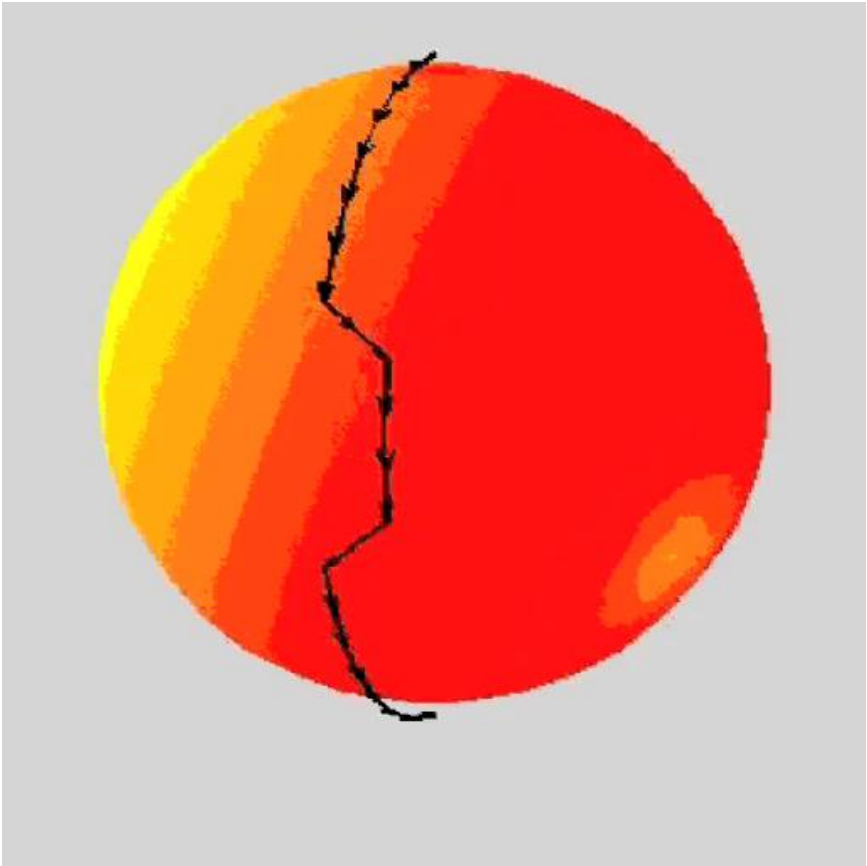
“poloidal (N-S) magnet

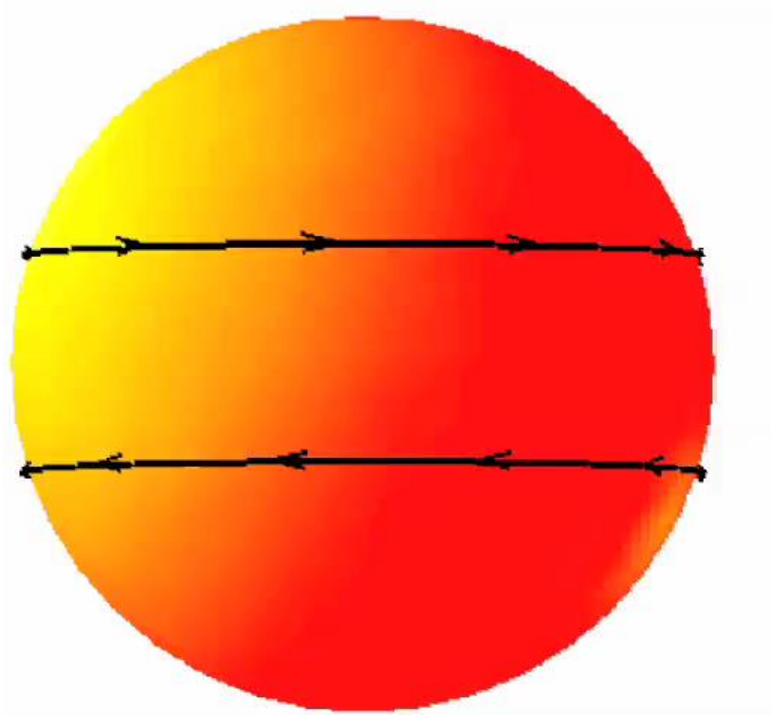
Hale 1 ct (1896)

Spo roidal (E-W) magnetic field”

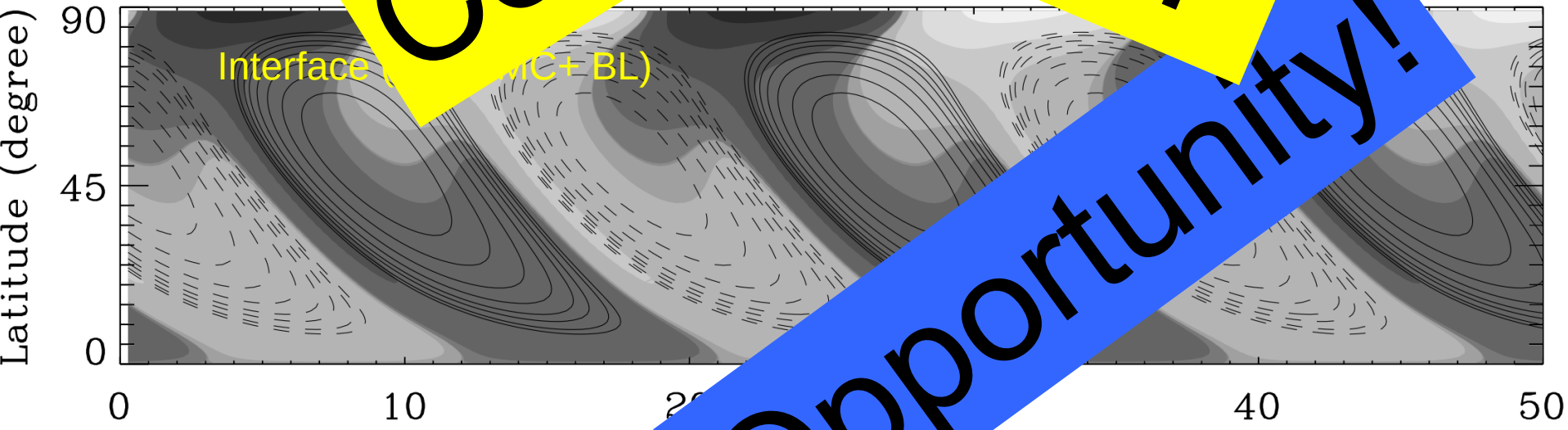
CYCLING

Ω, ⟨ effects





many dynamo types…



Transition
Horror story?
Comedy
Opportunity!

One of several processes that might contribute to the 22 year global magnetic cycle

Note
+ buoyancy=

flux emergence

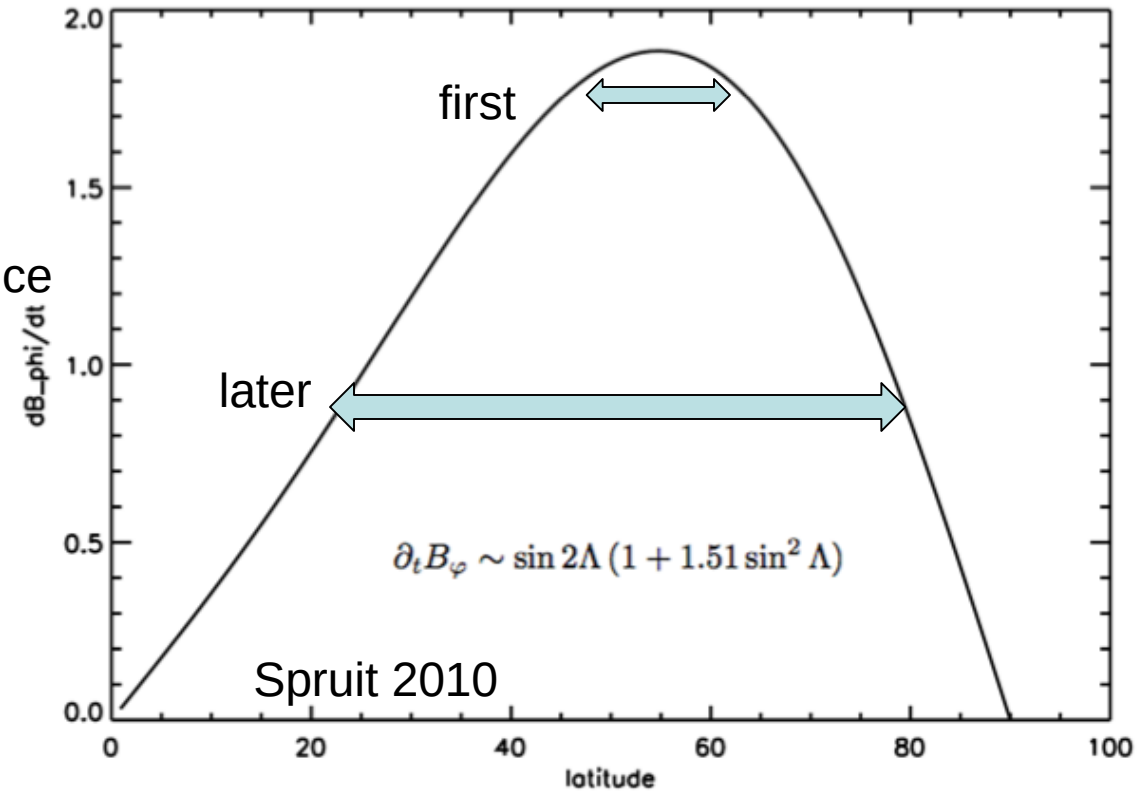


Figure 1: Rate of increase of the azimuthal field strength as a function of heliographic latitude, due to the observed differential rotation acting on an assumed uniform poloidal field.

-> Growth rate -> cycle period? Cf. Meridional circulation!

Summary of solar-only studies
Essential Ingredients in global solar dynamo models

- Rotation, differential rotation => strong toroidal field
- buoyant instability, flux rope rise
- toroidal -> poloidal source needed, MANY CLASSES, including
  - CZ α effect (non-linear)
  - surface α effect (Babcock-Leighton, B-L class)
- cycle closure requires reconnection across equator
- Near-ideal MHD accumulates helicity H= int **A.B**d^3r, sink required

Non-unique origins: macro- vs micro-physical

Quasi-linear macrophysics (B-L) vs. non-linear microphysics

(turbulent scales, α, η_T, …), *emergent behavior, complexity*

Summary

- Driving science questions
- The Sun in isolation
- The Sun as a star
- Conclusions

Accessible stellar observables of direct relevance to global dynamos

- Ground-based photometry, *milli-mag*, depending on *sin i,* through surface magnetic indices (Ca II, Stokes V,…), over decades
  - Rotation, DR
  - stellar cycle properties
  - flaring and spot/cycle activity

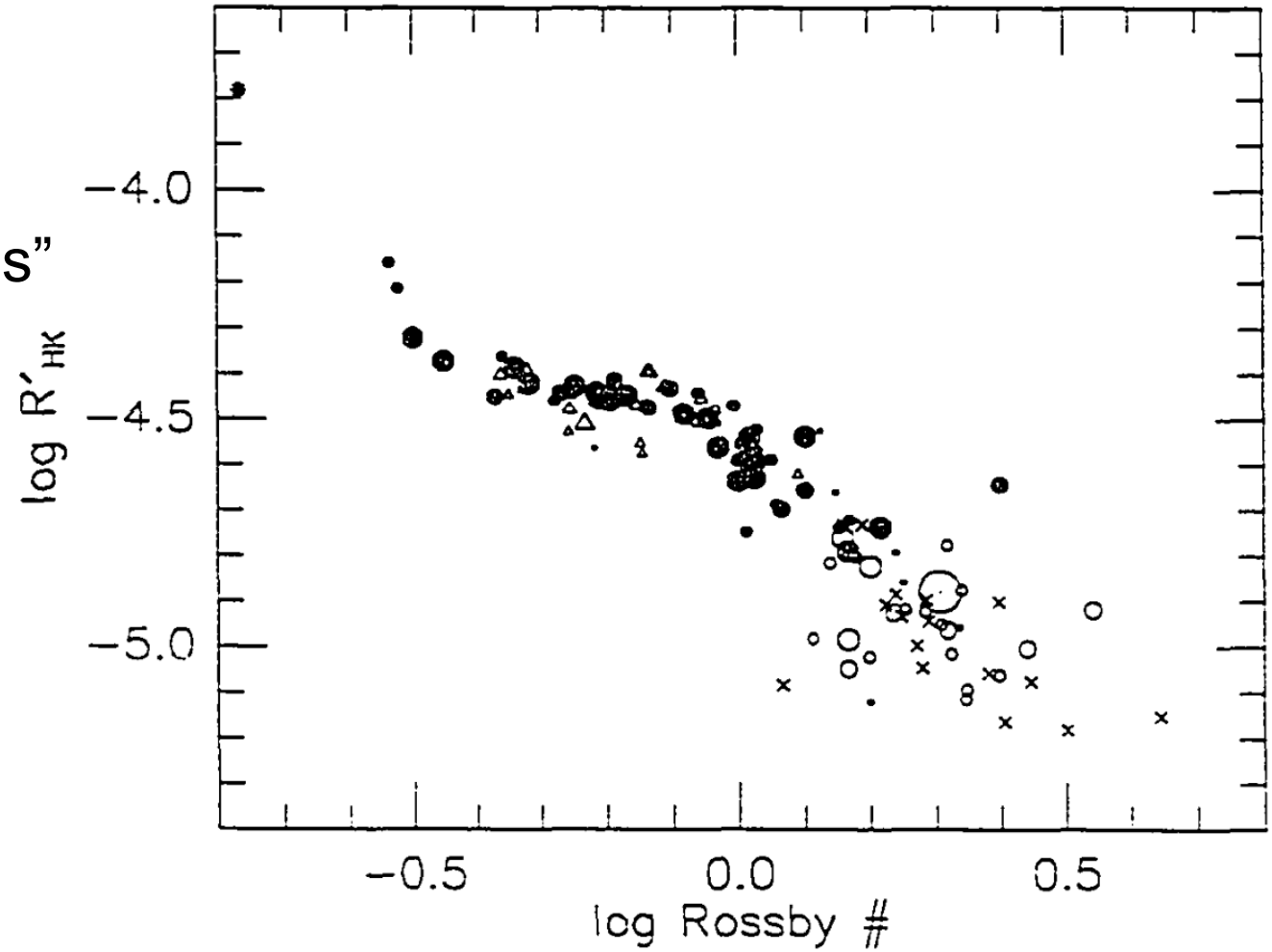
- Space (KEPLER quality) photometry, Kepler 17 (G2 V) + hot jupiter (Davenport et al)
  - spot longitudes, cycles, (latitudes), lifetimes, DR
  - surface diffusion rates, (meridional circulation)

- Soundings:
  - age, CZ depth, mean density,… (linewidths < 1 μHz) ~ month
  - solar-amplitude DR (< 0.01 μHz), ~ decade

Samples rotating stars, some fully convective, with access to DR, diffusion, (butterfly diagrams), polar reversals. Inaccessible: small-scale physics (= the Sun!), non-spot flux emergence, oscillatory DR, …

The Sun is not alone: chromospheric activity vs rotation and convection (Donahue 1993 Thesis)

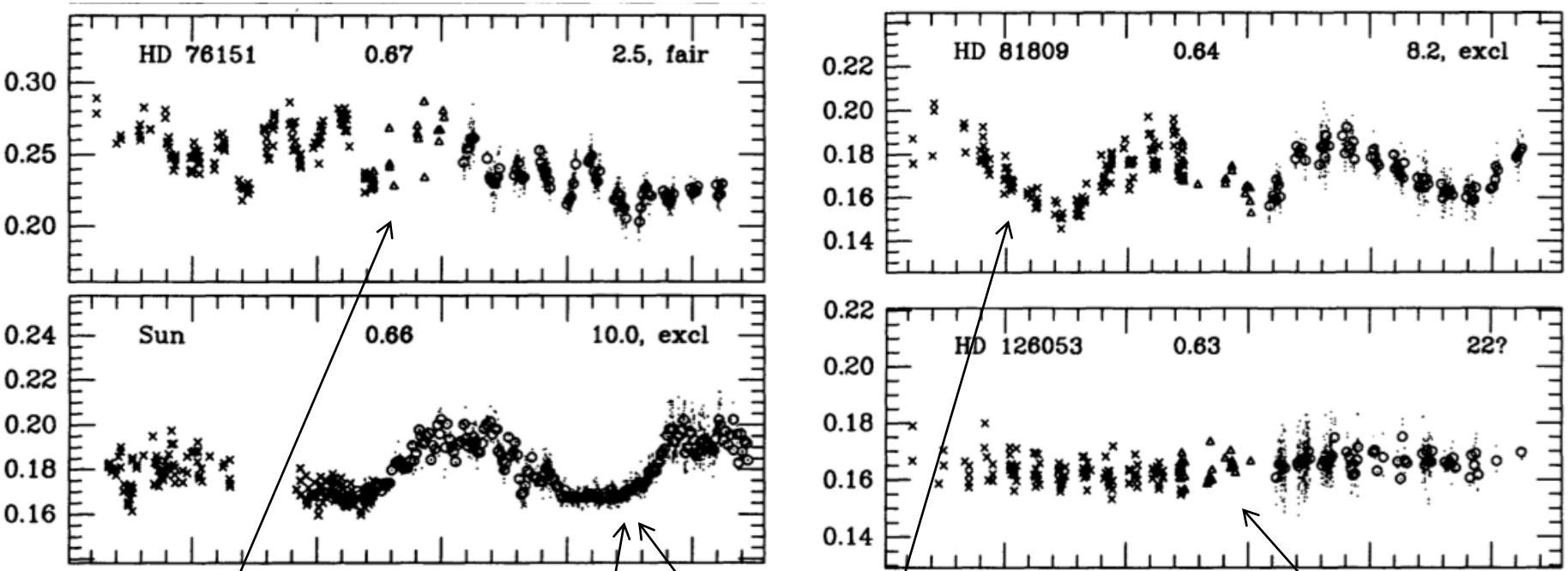
Ca II
"plages"



Ro= P_{rot}/τ_C, Dynamo number ~ Ro^{-2}

The Sun is not alone: global dynamos in Sun-like stars

Baliunas et al 1995: The Sun is a typical middle aged star: Almost as many such stars don't "cycle" as do.



1966

1993

Irregular, "chaos"?

Varies with sunspot number

Cycling: order from chaos

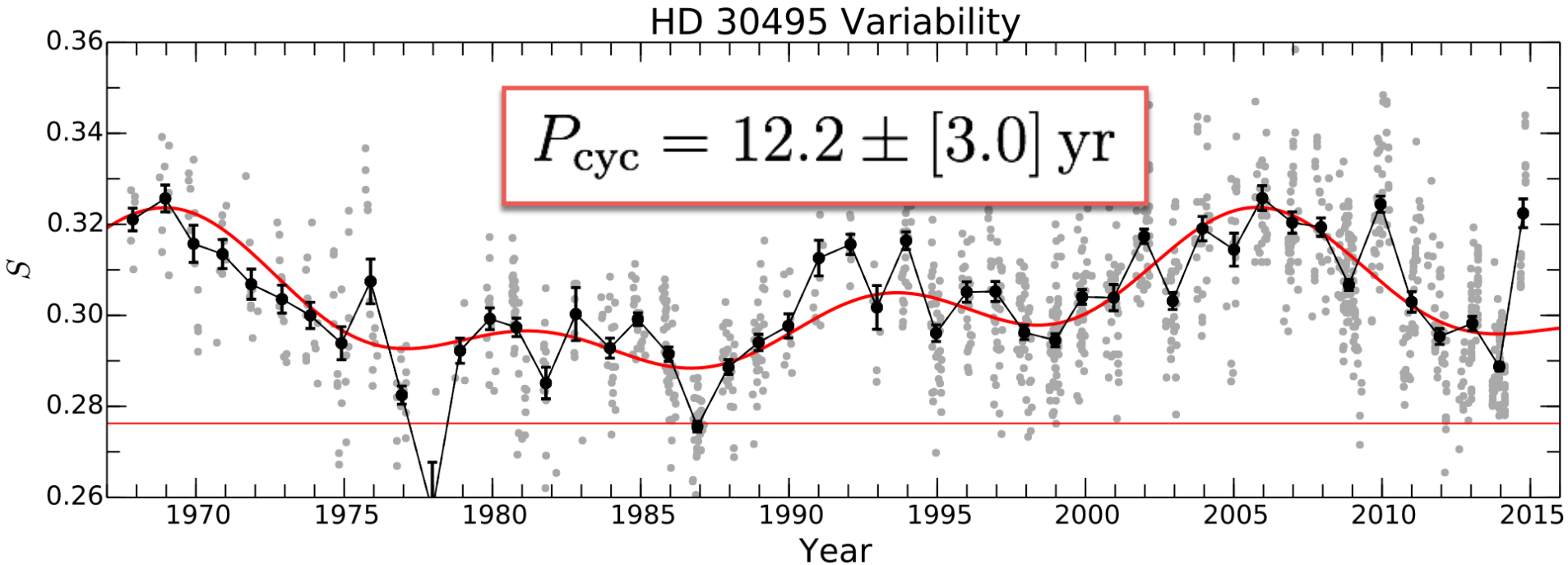
Flat

A Case Study: HD 30495

(Egeland et al 2015 ApJ)

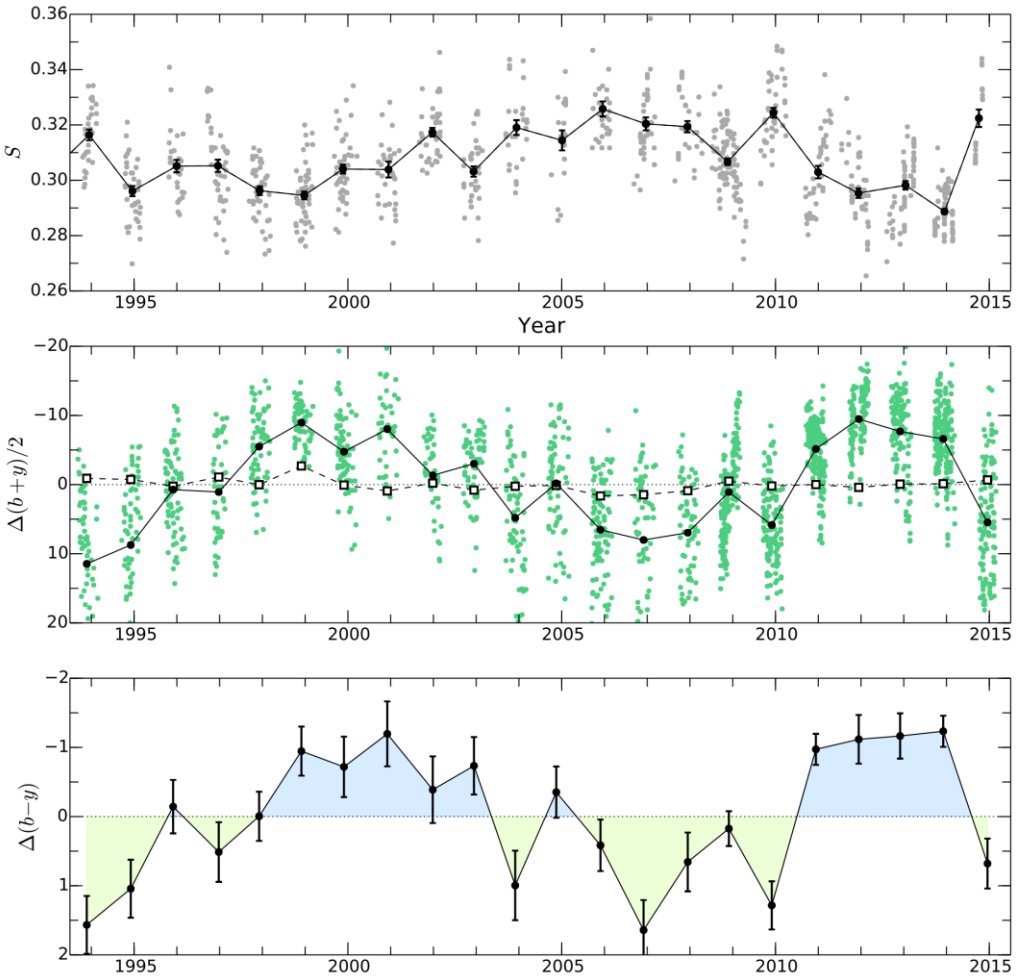
Property	Value	Reference	
Spectral type	G1.5 V	(1)	G2 V
V	5.49 ± 0.01	(2)	-26.7
B-V	0.632 ± 0.006	(2)	0.65
Parallax	75.32 ± 0.36 mas	(2)	
$v \sin i$	4.1 ± 0.8 km s^{-1}	(3)	
$T_{\rm eff}$	5826 ± 48 K	(4)	5770
$\log g$	4.54 ± 0.012 dex	(4)	4.44
[Fe/H]	$+0.005 \pm 0.029$ solar	(4)	0
Mass	$1.02 \pm 0.01\, M_\odot$	(4)	1
Radius	$0.898 \pm 0.013\, R_\odot$	(4*)	1
Luminosity	$0.837 \pm 0.037\, L_\odot$	(4*)	1
Age	970 ± 120 Myr	(5*)	4500 Myr
$\overline{P}_{\rm rot}$	11.36 ± 0.17 days		
ΔP	0.59 ± 0.05 days		
$\Delta\Omega$	$\gtrsim 1.67 \pm 0.15$ deg/day		
$\sin i$	1.0 ± 0.2		
i	$\gtrsim 55.4°$		
$P_{\rm cyc,long}$	$12.2 \pm [3.0]$ yr		
$A_{\rm cyc,long}$	$0.118 \pm [0.044]$		
$P_{\rm short}$	$1.67 \pm [0.35]$ yr		
$A_{\rm short}$	$0.066 \pm [0.028]$		

47 year time series HD 30495 MWO+SSS



Cycle	Start	Max	Duration	$S_{\rm max}$	$A_{\rm cyc}$
0	(1961.7)	1969.0	(15.3)	0.324	0.156
1	1977.1	1981.2	9.6	0.297	0.067
2	1986.7	1993.7	11.7	0.305	0.095
3	1998.4	2005.8	15.5	0.324	0.156
4	2013.9	–	–	–	–

APT Photometry (Fairborn Observatory)



Activity-brightness anti-correlation
→ spot dominated

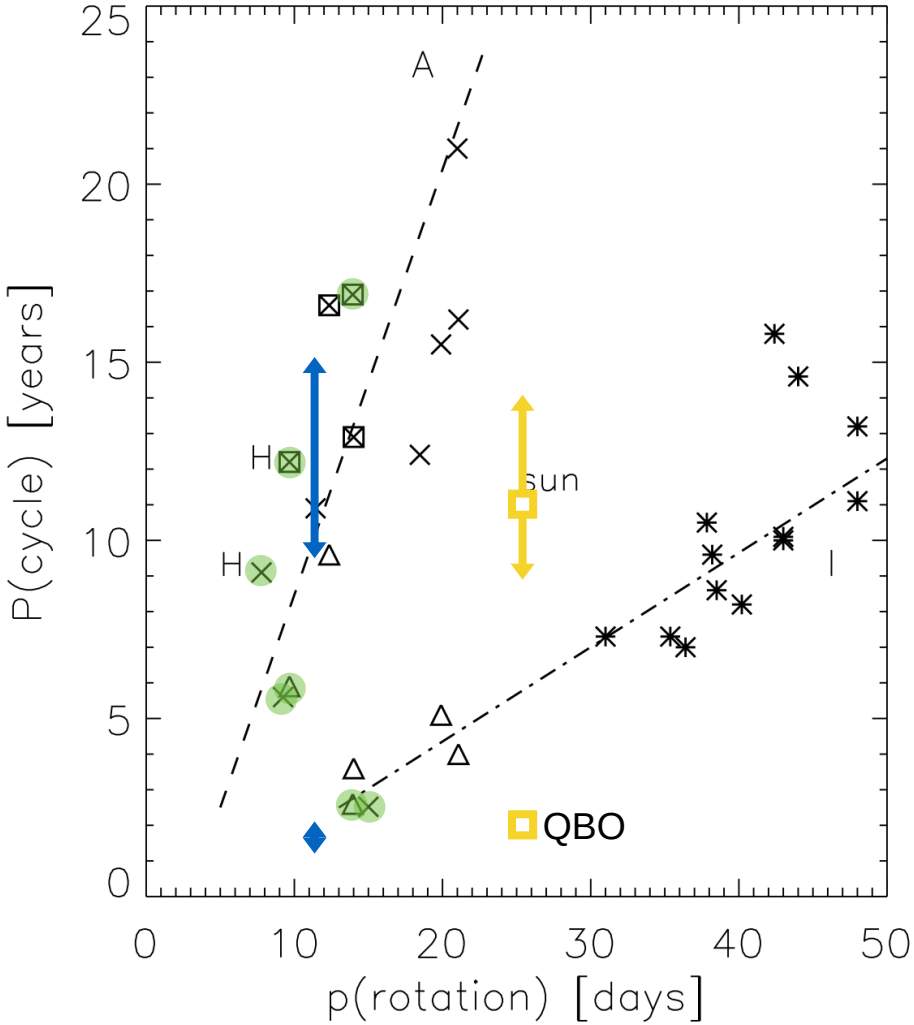
Significant rotation signal in 17/22 seasons:

$$\overline{P}_{\rm rot} = 11.36 \pm 0.17\,{\rm days}$$

$$\Delta P = 0.59 \pm 0.05\,{\rm days}$$

$$i = 90 \pm 35\,{\rm deg}$$

P_{cyc} vs. P_{rot}, differential rotn



HD 30495

G0 – G5 type

$$\overline{\Omega}_\star = 31.7 \pm 0.5\,\mathrm{deg/day}$$

$$\overline{\Omega}_\star / \overline{\Omega}_\odot \approx 2.3$$

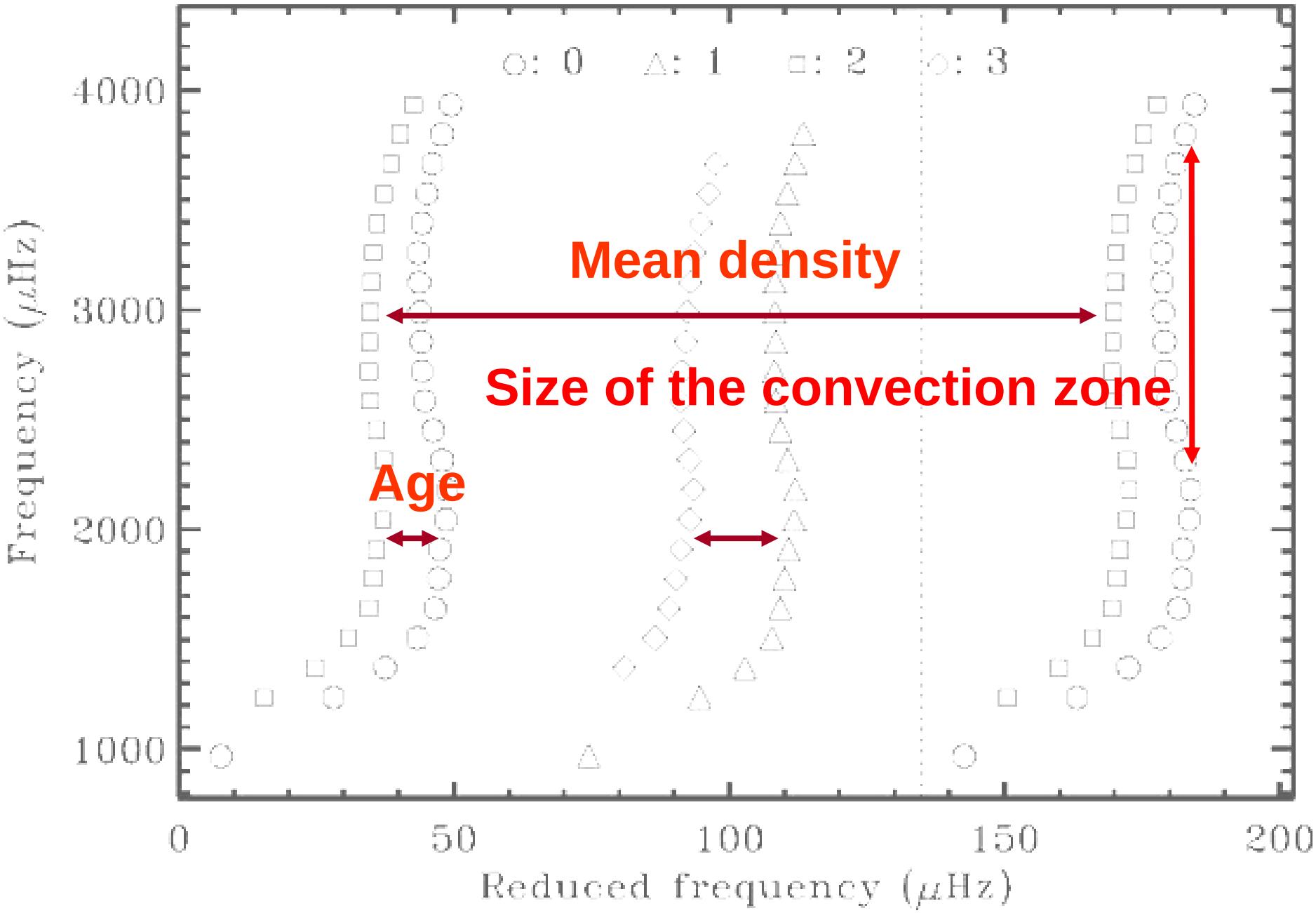
$$\Delta\Omega \gtrsim 1.67 \pm 0.15\,\mathrm{deg/day}$$

$$\frac{\Delta\Omega_\star}{\Delta\Omega_\odot} \geq 0.40 \pm 0.03$$

$$\frac{\Delta\Omega_\star}{\Delta\Omega_{45,\odot}} \geq 1.02 \pm 0.09$$

Böhm-Vitense 2007

Soundings (asteroseismology)


○: 0
△: 1
□: 2
◇: 3
Mean density
Size of the convection zone
Age
4000
3000
2000
1000
Frequency (μHz)
0
50
100
150
200
Reduced frequency (μHz)

Differential rotation: C. Karoff

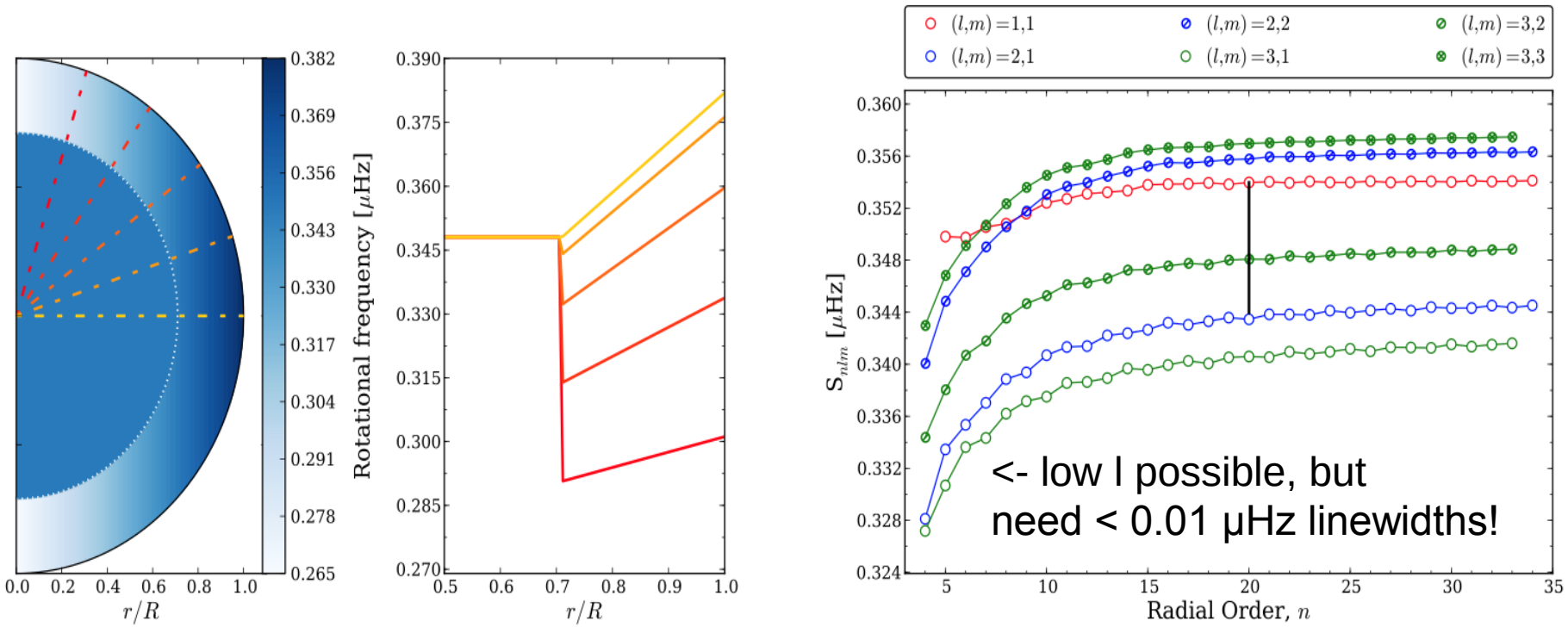


Figure 15. Left: *Rotation profile for a star rotating with a cylindrical profile, and solar-like in the sense that the equator is rotating faster than the poles. The small left panel give the 2D rotation profile of the star, while the 1D rotation profiles are given in the small right panel for the subset of co-latitudes indicated on the 2D rotation profile.* **Right:** *Calculated frequency splittings as a function of radial order for the cylindrical rotation profile in the left panel and the rotation kernels computed from the adopted model star. The solid vertical reference bar at n = 20 shows the extent of a 0.01 μHz frequency difference.*

Kepler quality photometry: J. Davenport et al 2015

Spot+transit technique (restricted latitiude information)

Kepler 17 (G2 V) + hot jupiter, P_{orb}=1.5d, P_{rot}=12.1 d, ratio 1:8

- Solve for spot properties on the surface over 4 years.
- O(100) spots
- Spot size & longitude, magnetic surface diffusion timescales
- Spot DR: $P(\varphi)=P_{eq}/(1-k\sin^2\varphi)$ k=0.8

  cf. Sun k=0.2, M4 star k=0.0001

Kepler 63 might get latitude and longitude of spots, get sign of DR.

CONCLUSIONS

- Observations show unreasonable order in the Sun's magnetism

- Multiple "successful" solar dynamo models are compatile with data

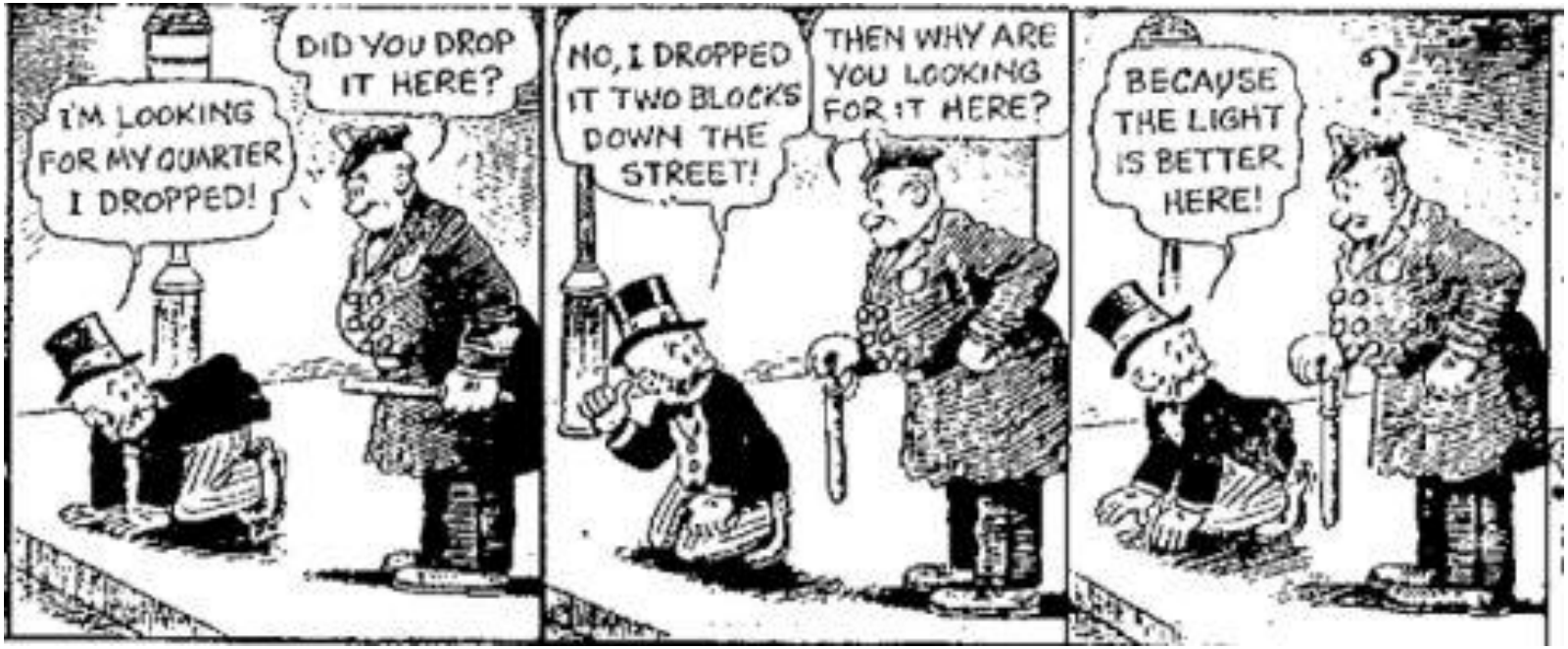
- Simulations are difficult, incomplete, in inaccessible regimes. MHD issues
    - Frameworks (mean field, non linear, flux transport, origin of α)
    - Constants of motion (accumulation of helicity), diffusivities
    - Sunspot formation

- This must be an observationally driven research area.

- We have vast archives of solar data (eg. SoHO, SDO, Gong, Bison,…), and
- 50 year timeseries of stellar activity
- More stellar data and analyses are needed, and should include
    - Fundamental parameters
    - Rotation -> coriolis force -> α
    - Differential rotation -> Ω
    - Surface and interior circulation [macro-] or diffusion [micro-/macro]
    - Spot data

- We should try to reject classes of dynamo models using solar and stellar data

Postscript



…Just because the sun is bright does not mean we will answer important questions under its own light, alone

and the same goes for stars

Particular thanks to

Mausumi Dikpati, Matthias Rempel, Travis Metcalfe
Christoffer Karoff

Newkirk Fellowship program at HAO, NCAR