THE SUN

The mercurial star at the heart of our solar system

Philip Judge

January 2021

NCAR

High Altitude Observatory

NSF

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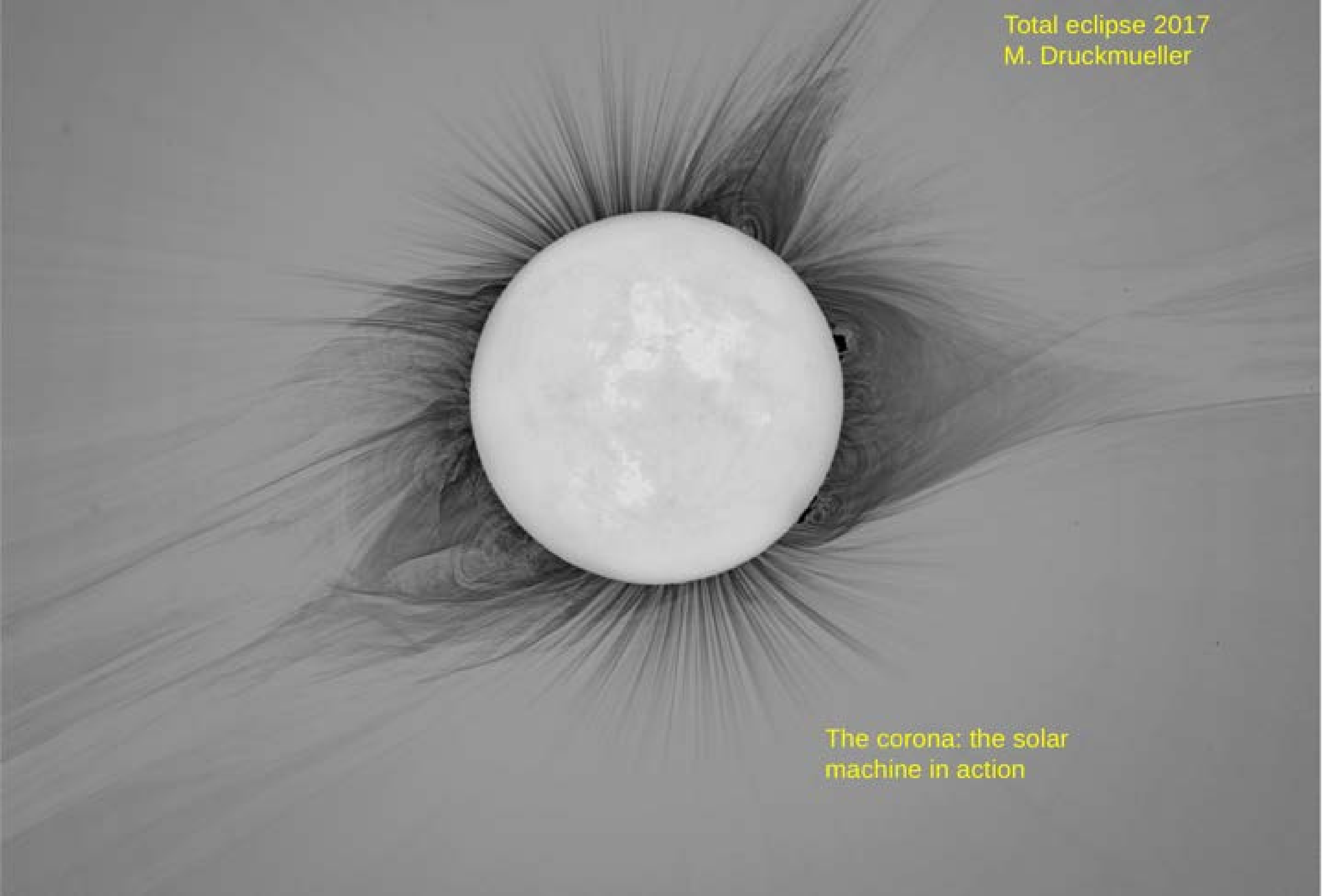
Goal of this talk

Review the Sun's history from a planetary perspective

- Zero-Age main sequence to the present day & beyond
- Galactic and stellar context
- [Planetary connections]
  - Life origins
  - Climate
  - Modern society
  - Too complex

Leitmotif:

Convection+rotation =>
the Sun is a *magnetic* machine
that generates fast
fluctuations and emissions
with energies >> 0.5 eV

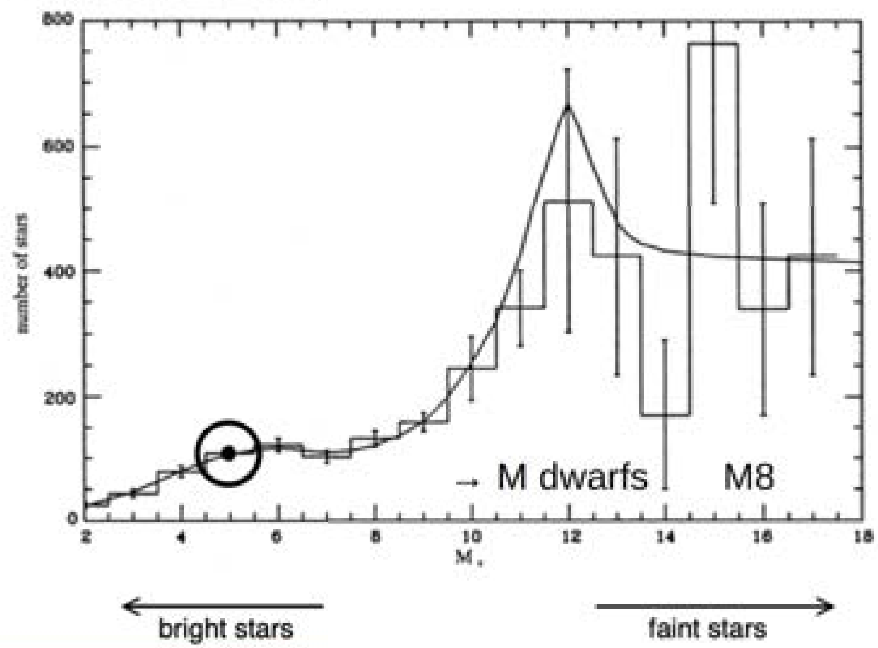

Total eclipse 2017
M. Druckmueller
The corona: the solar
machine in action

Galactic and stellar context

- Does not belong to a stellar group
- similar to stars in M67

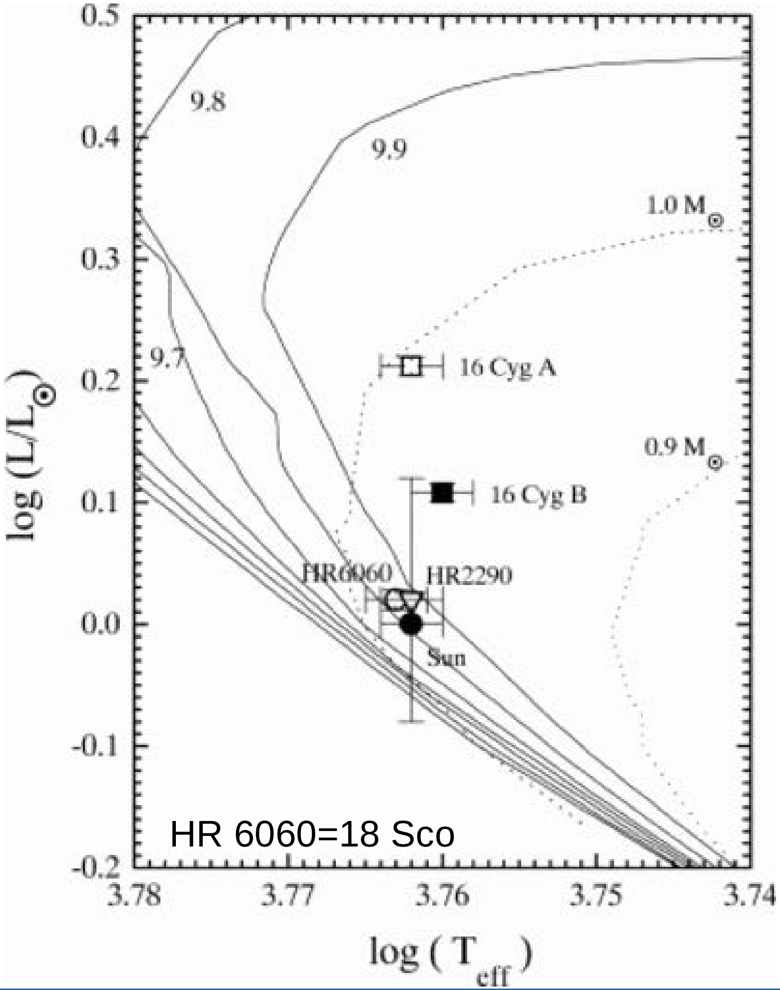
- Solar ``twins'' 18 Sco = HD 146233
  recently (2018) HD 186302

Local luminosity function (stars with d < 20 pc) for the Milky Way measured by Kroupa, Tout & Gilmore (1993):



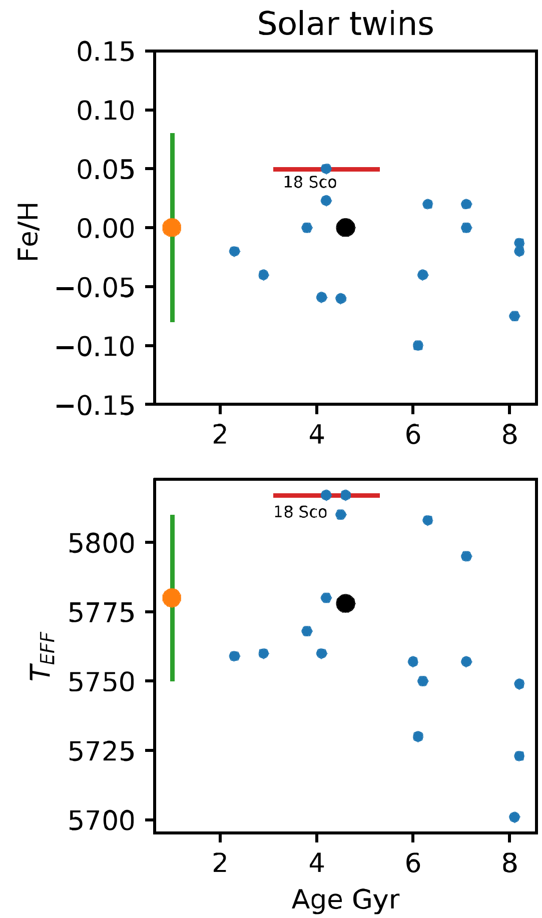
^{235}U on Earth r-process contamination from SN → ⊕ core heat → ⊕ magnetism

Solar twins are surprisingly rare (depending on your selection criteria)



But data are steadily improving through astroseismology (KEPLER, TESS, ...)

Wikipedia



Galactic and stellar context

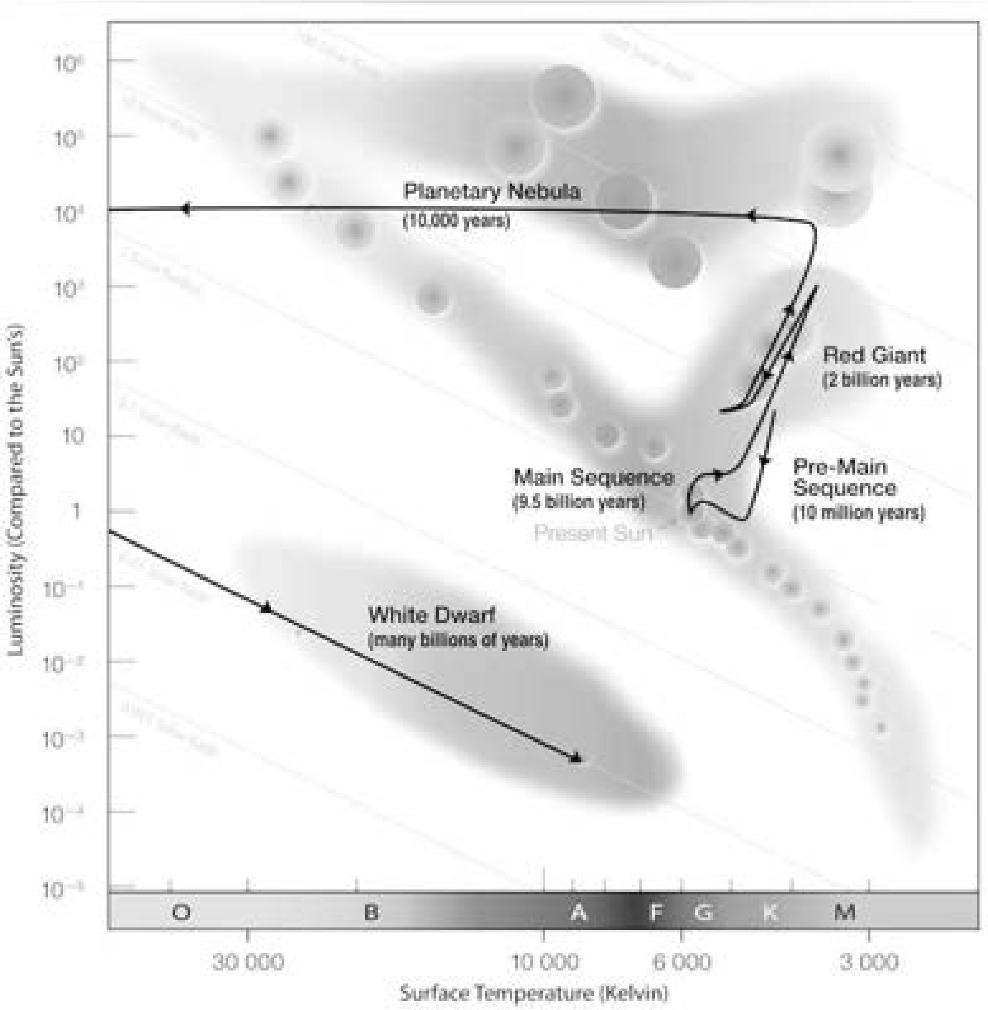


Table 1. Some basic properties of the Sun

Mass ($M_\odot$)	**2×10^{30} kg**
Radius ($R_\odot$)	700,000 km ≡ 1 AU
Distance	150,000,000 km
Luminosity ($L_\odot$)	4×10^{26} W
Irradiance at Earth	1.365 kW/m^{-2}
Average rotation period	27 days
Stellar spectral type	G2 V

Notes: kg=kilograms, AU=astronomical unit, km=kilometres, W=Watts, kW=kiloWatts, kW m^{-2}=kiloWatts per metre^{-2}.

Age at present 4.5 Gyr

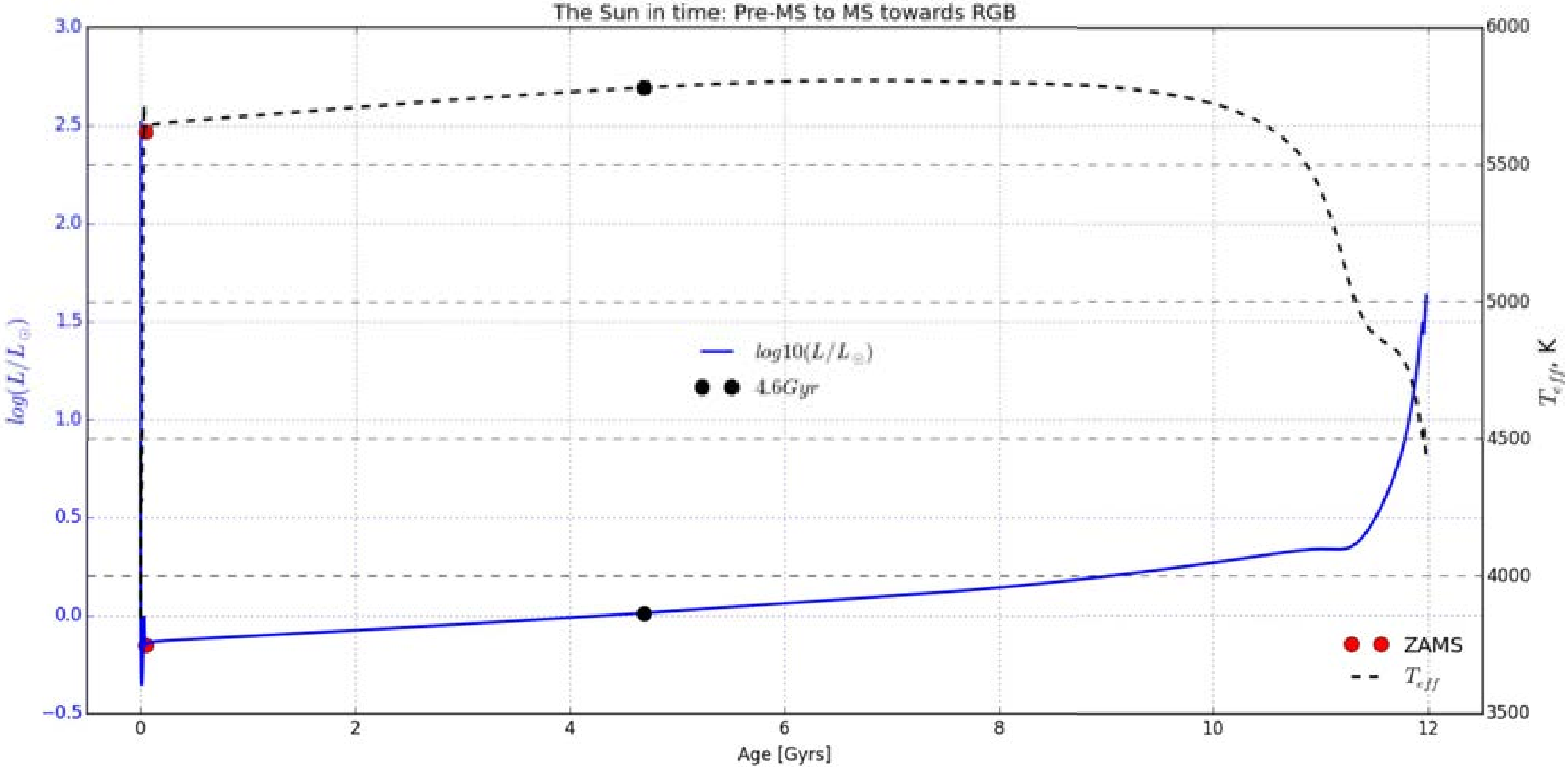
Table 2. Relative solar and terrestrial element abundances

Element	Solar abundance (by number %)	Crustal abundance
H	93	3
He	7	3×10^{-6}
C	0.03	0.3
N	0.009	0.14
O	0.07	60
Ne	0.007	3×10^{-7}
Si	0.004	20
Fe	0.003	2.3

Notes: H=hydrogen, He=helium, C=carbon, N=nitrogen, O=oxygen, Ne=neon, Si=silicon, Fe=iron. Data are taken from taken from webelements.com

Middle-aged, pop I star

Galactic and stellar context

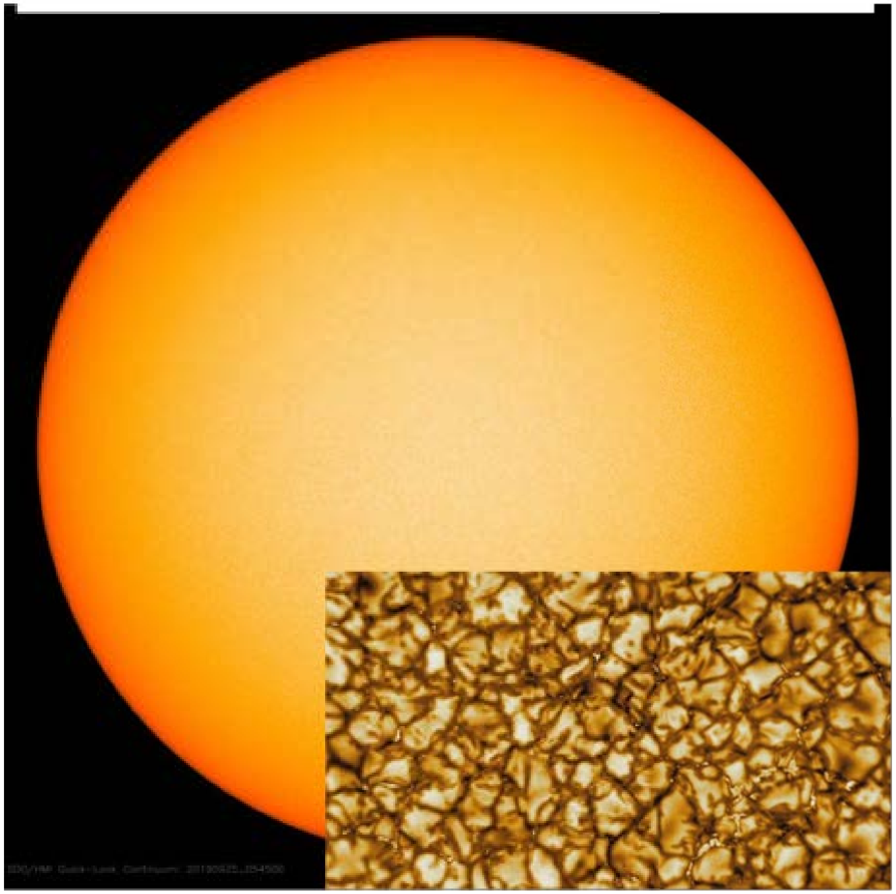


stellar context
is the Sun an Oddball?

Not really... more later as we must review the fact that the Sun is, unexpectedly, a magnetic machine.

A star built from first-principles

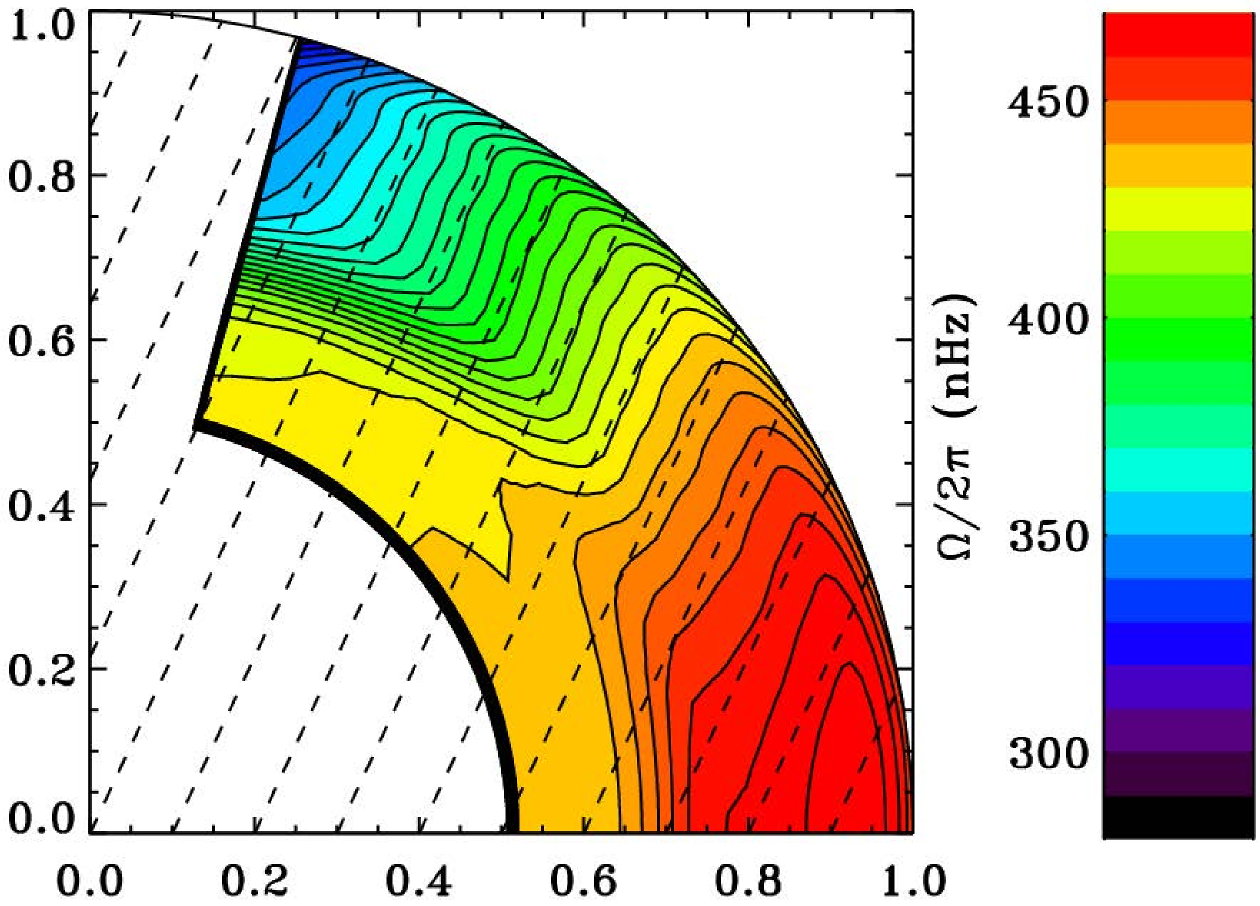
$$T(\tau) \approx T_{\text{eff}} \left(\frac{3}{4}\tau + \frac{1}{2} \right)^{1/4}$$



← Surface convection

Normal modes of oscillation

A star built from first-principles



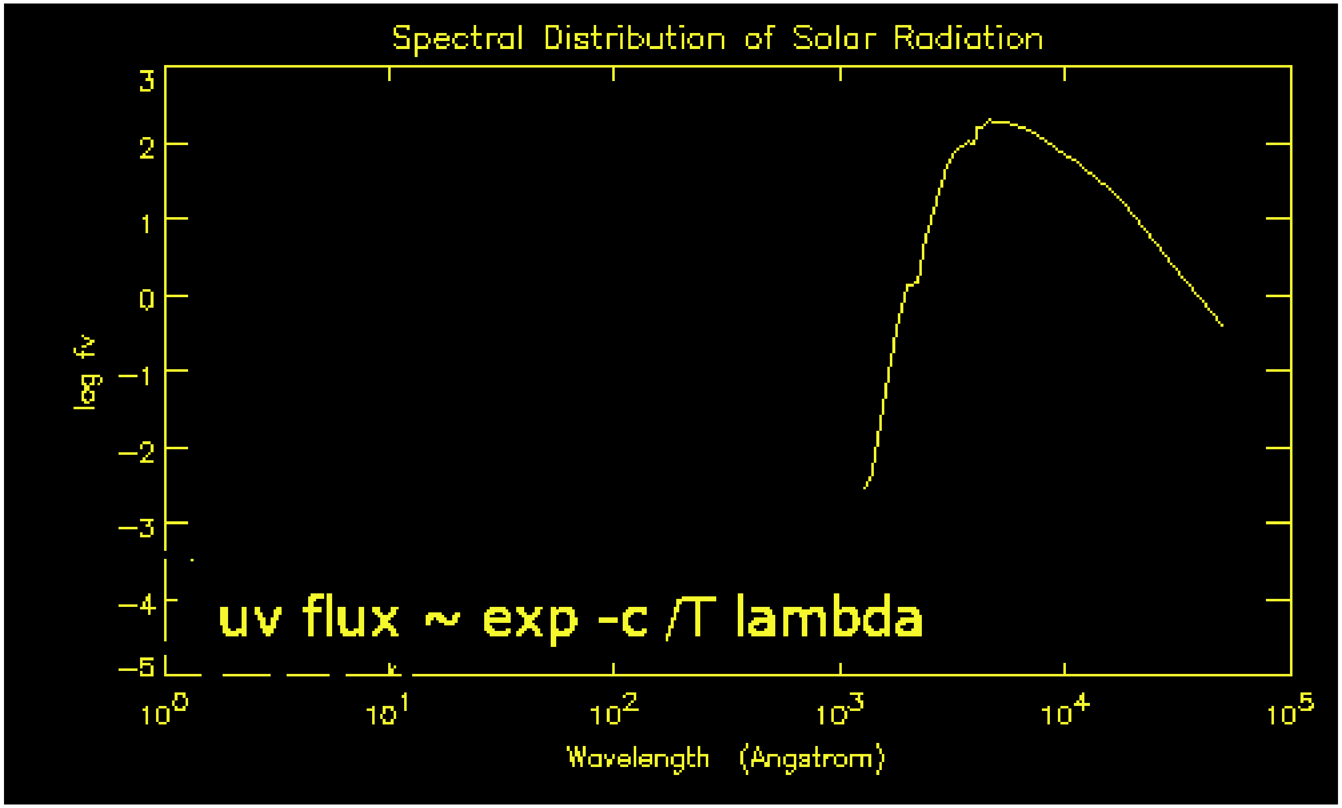
Differential rotation-

this image is not theoretical but obtained by ``sounding'' the Sun.

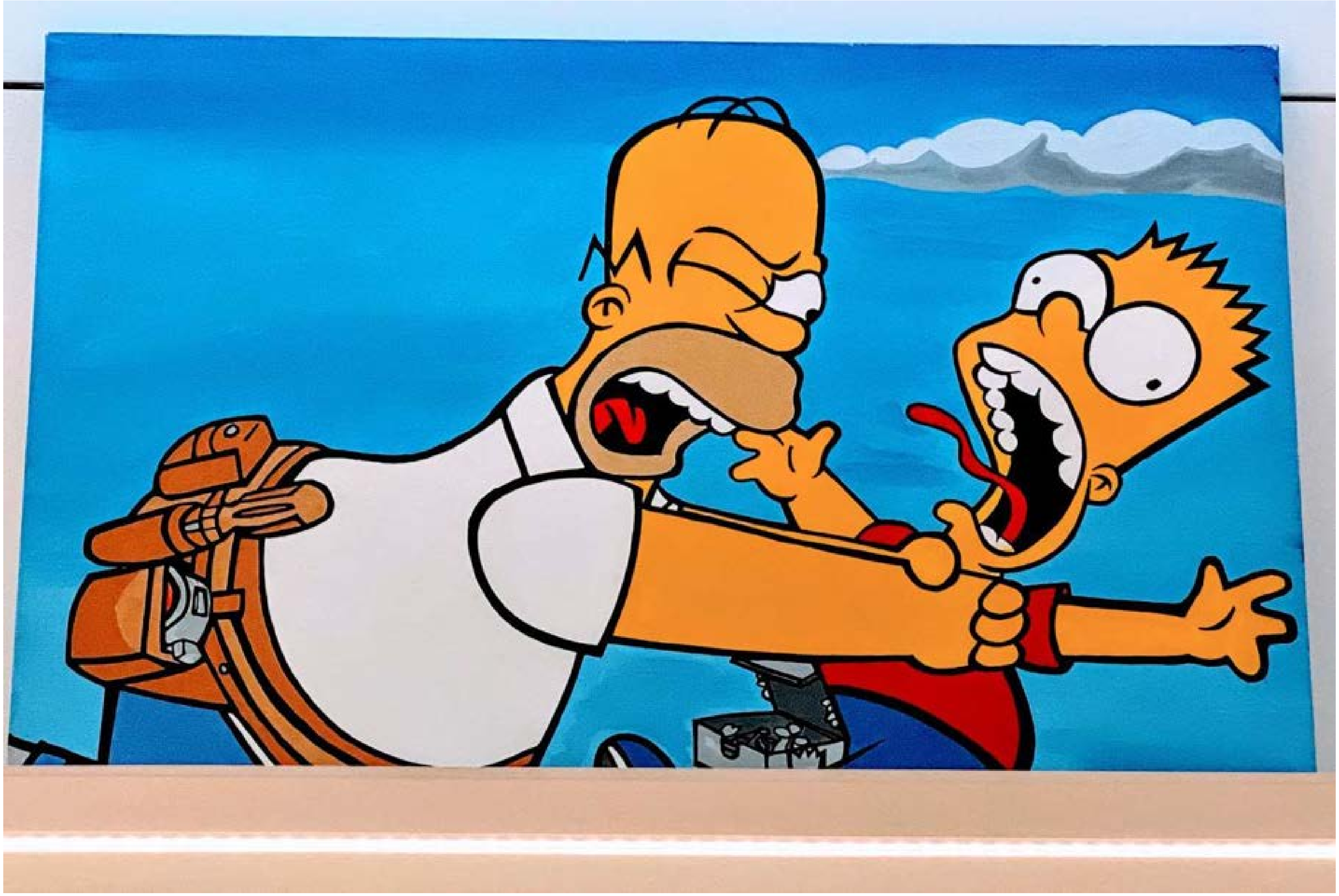
It contradicted many theoretical ideasl

a CRITICAL parameter in our story

A star built from first-principles



outrageous behavior



Outrageous solar behavior

Image fades between photosphere ($0.8T_{EFF}$) and corona ($> 200T_{EFF}$!)

We are **accustomed** to seeing how the Sun behaves. But why must it behave so?

Wigner's dictum: *The important problems in physics are rarely solved; they are either forgotten or declared to be uninteresting*

NCAR

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

The remarkable case of global solar magnetism

The Sun is a stable nuclear processor.

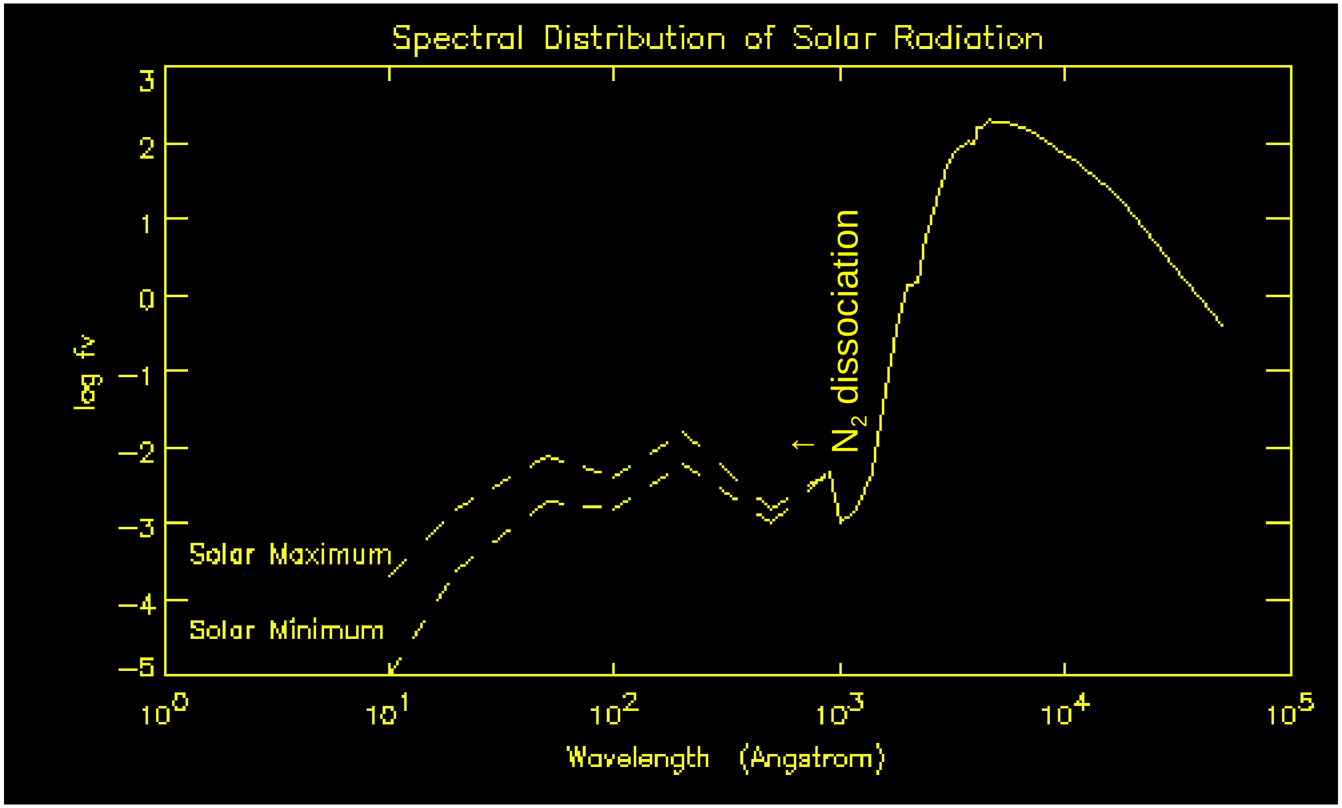
From first principles (up to 1930s),

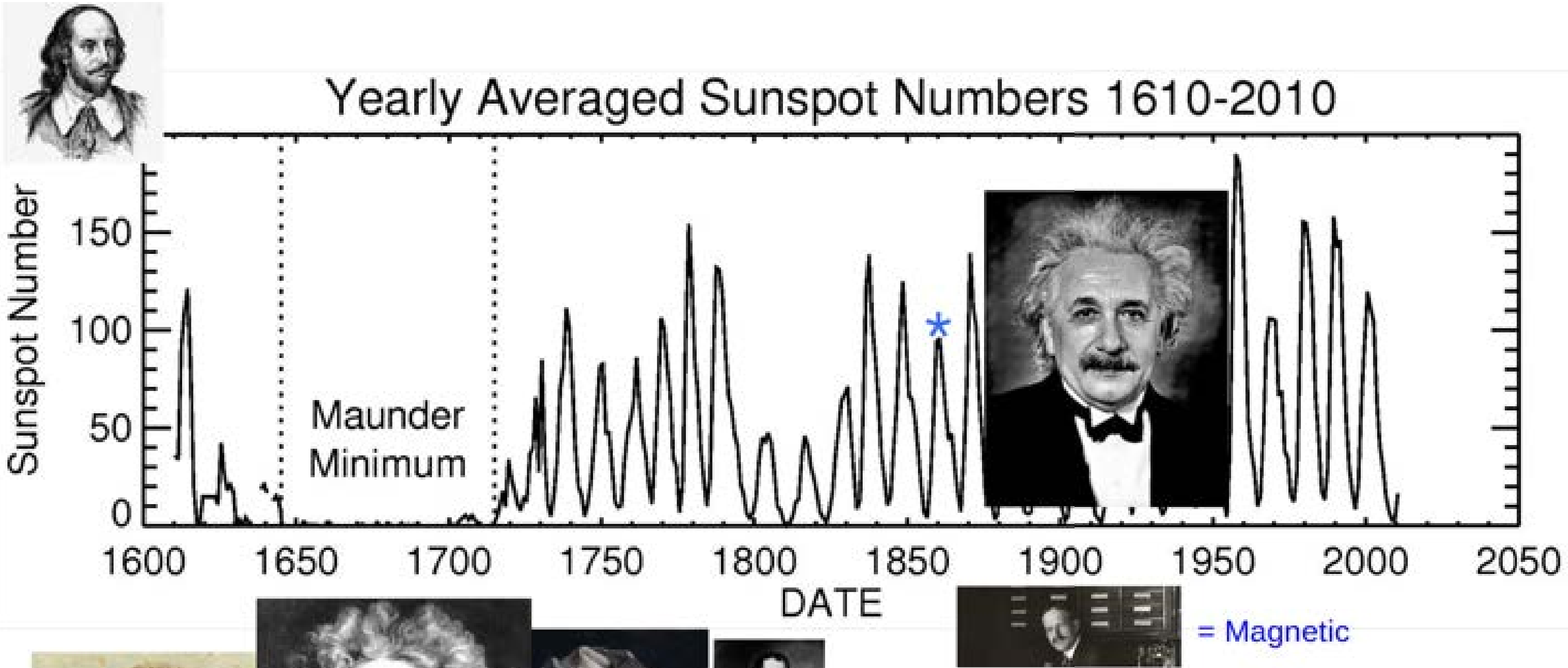
- expect global time scales $E / \dot{E} \geq 10^5$ yr (Kelvin-Helmholtz) or ~ 10^9 yr (nuclear)
- locally chaotic motions (convection), global oscillations (stars)
- Almost a black body spectrum (5775 K ~ 0.5 eV)
- No significant magnetic or electric fields
  - maybe long-lived “turbulent” magnetic fields (1940s)

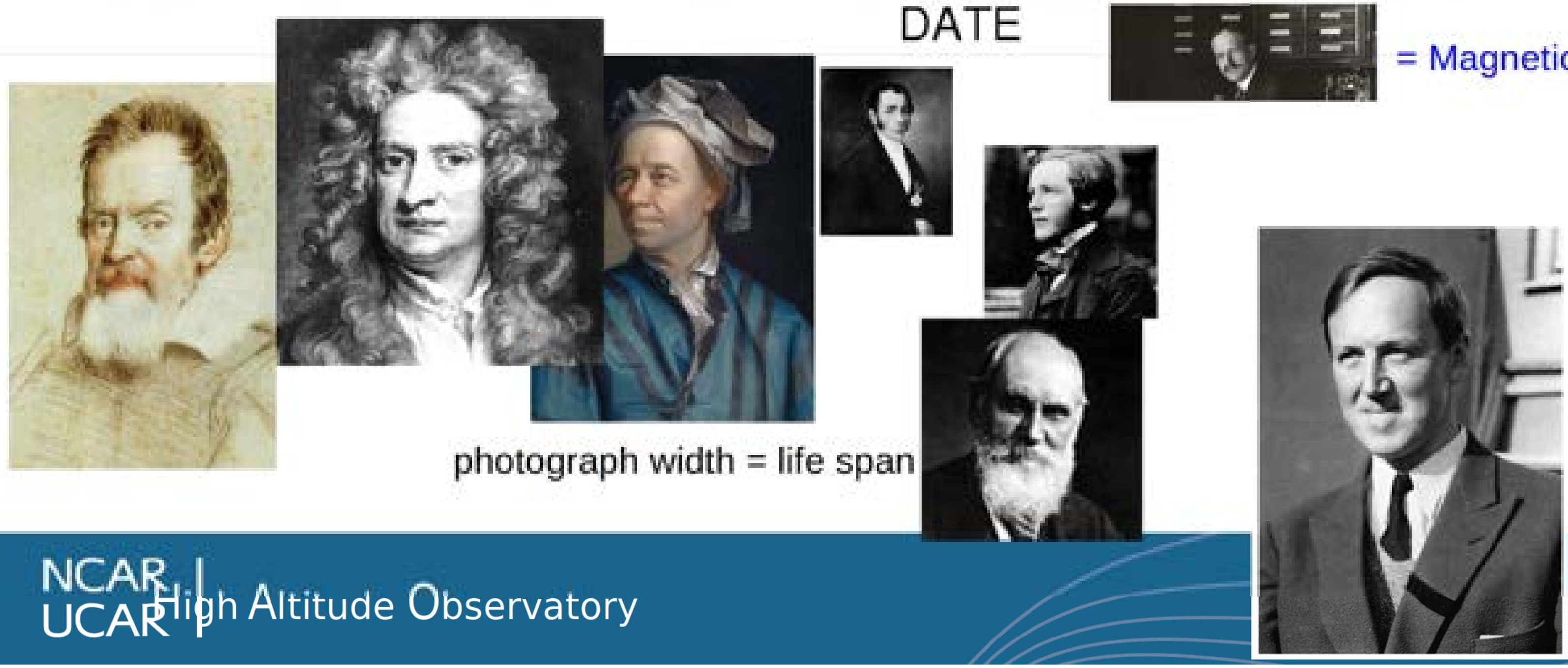
Instead we see ***rapid changes*** and ***order from chaos*** presenting us with well-known but ***unsolved*** problems

- Magnetic field regeneration (“dynamo”)
- dissipation (“coronal heating”)
- **“activity” = effects of magnetic fields**

A convecting, rotating star
the Sun




Yearly Averaged Sunspot Numbers 1610-2010
Sunspot Number
0
50
100
150
Maunder
Minimum
*
1600
1650
1700
1750
1800
1850
1900
1950
2000
2050
DATE
= Magnetic


photograph width = life span

Sunspots: order from chaos

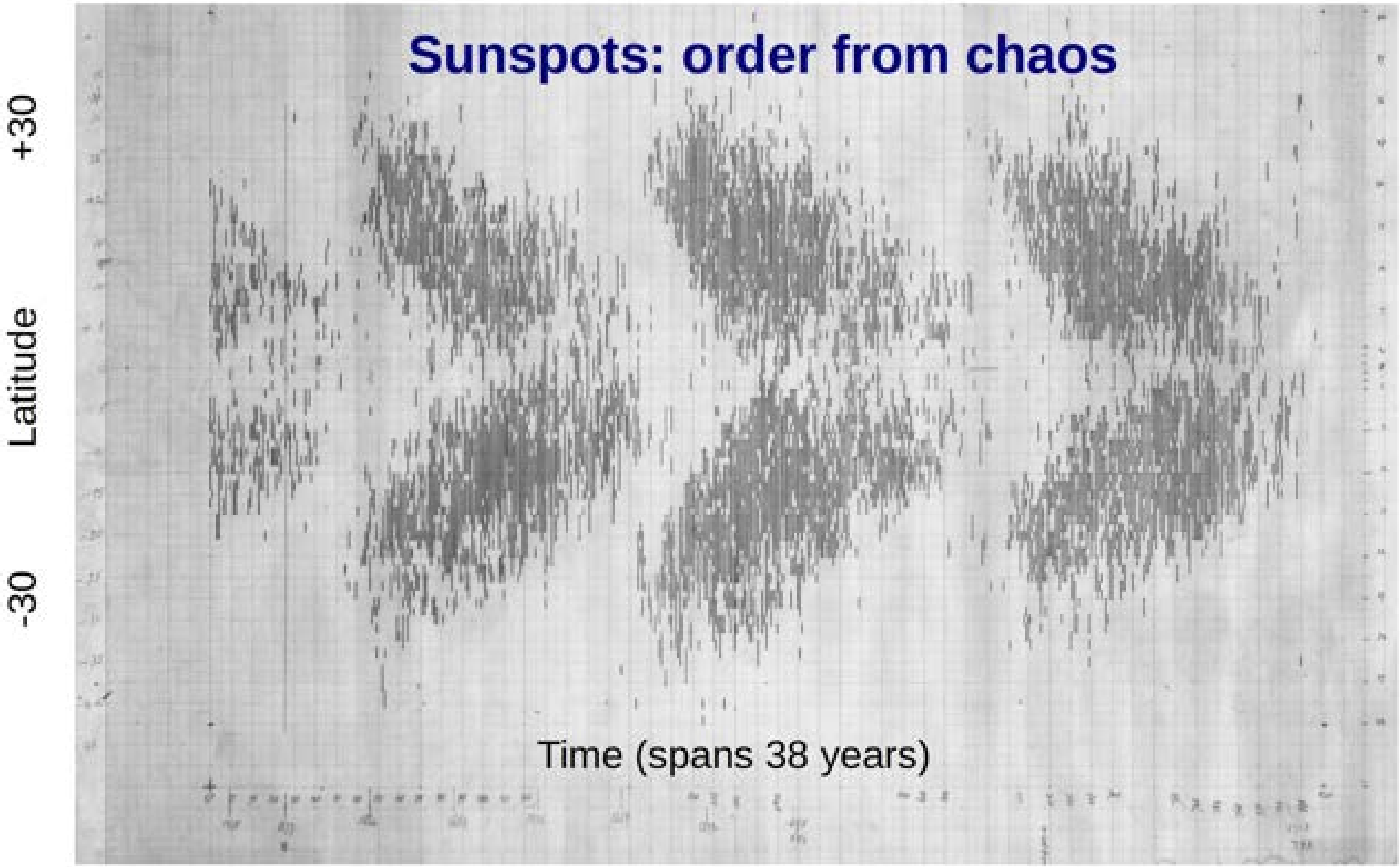
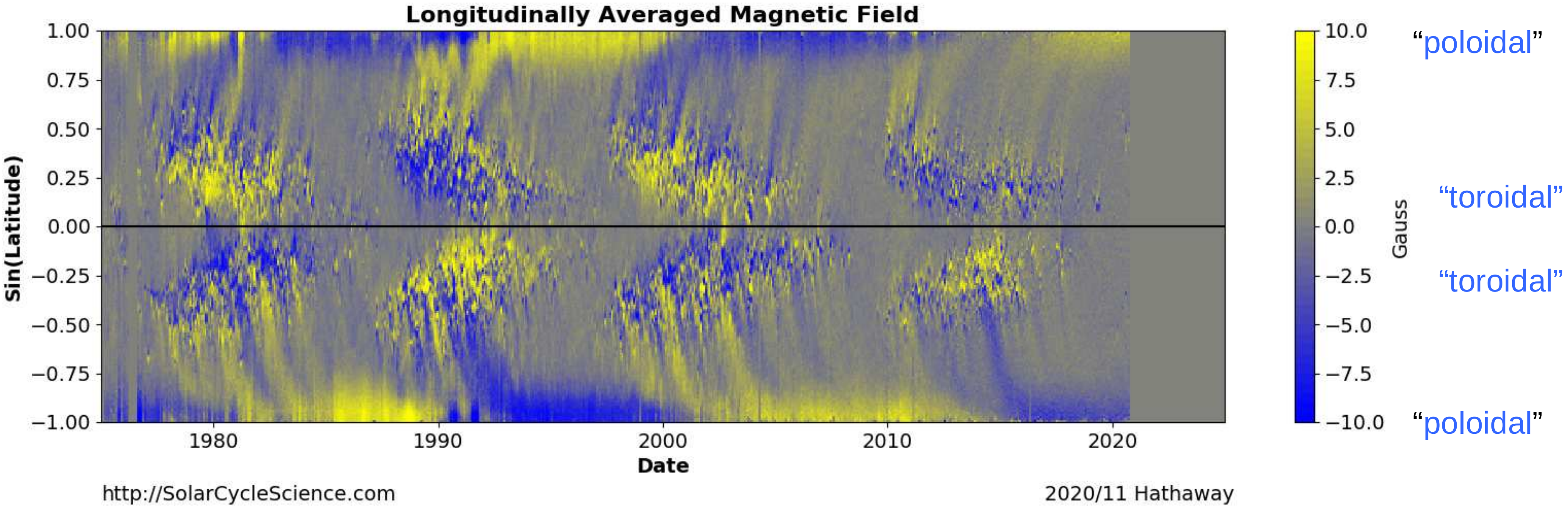


Figure 1.2 Time-latitude “butterfly diagram” drawn by Annie S.D. Maunder and E. Walter Maunder. The longitude-averaged sunspot data goes from 1875 to 1913, covering solar cycles 11 (partial) through 14.

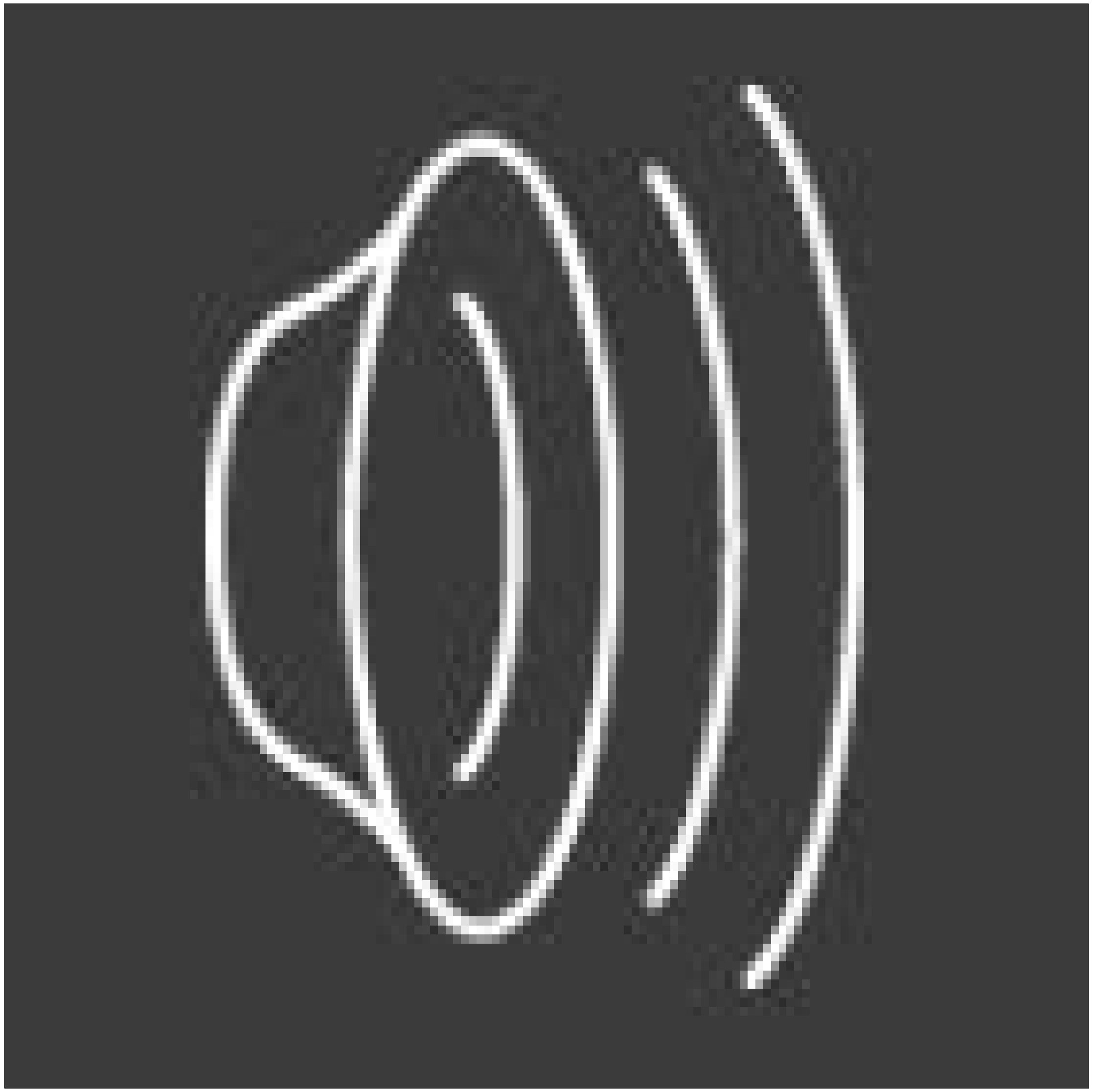
“Order from chaos”
toroidal (spots) and poloidal magnetic structures



Line of sight magnetic fields only (circular polarization)

Magnetic energy storage and explosive release

X7 flare by SDO on Aug. 9, 2011
(90 min sequence)



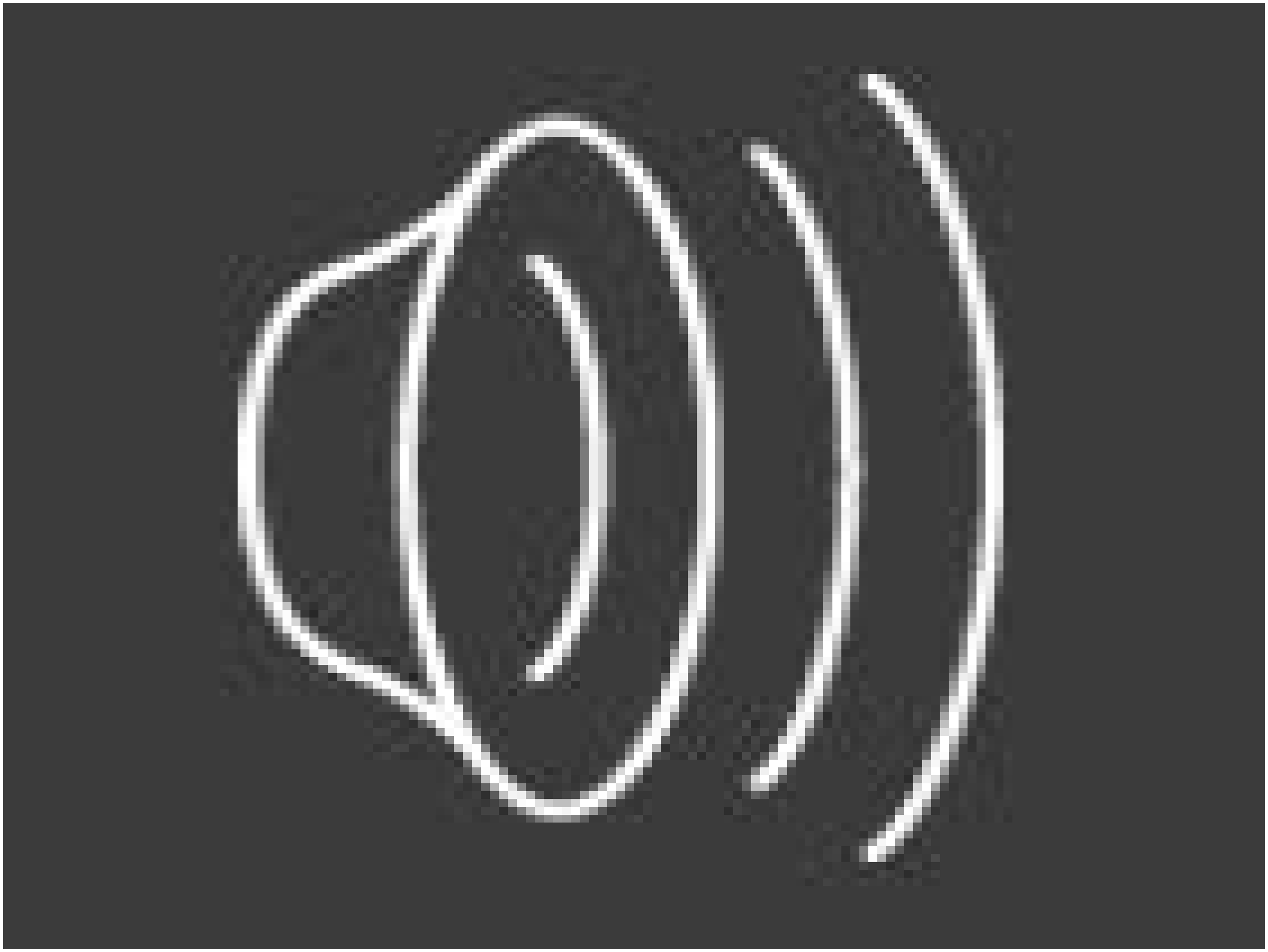
Magnetic energy storage and explosive release

Ejection of
hot plasma

flaring

X- and ***γ***- rays

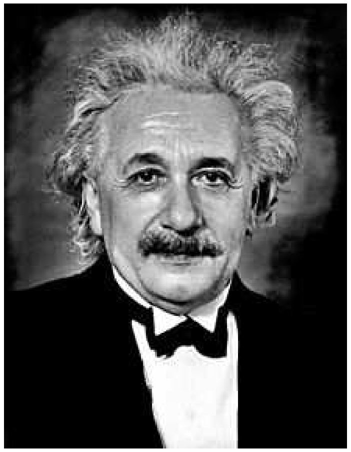
particles and
radiation in
interplanetary
space



Why is this outrageous?

- some physics

Magneto-Hydro-Dynamics "MHD"



Einstein changed Newton's formulation to fit Maxwell's equations.

He got a Nobel Prize, but not for this.

MHD can be thought of as the reverse applied to a conducting fluid: Change Maxwell's equations, with field and plasma transformations including O(v/c) to fit Newton's laws of motion.

Originally formulated by H. Alfvén in the 1940s and 1950s, he won a Nobel Prize for this and related work.

It is the simplest model of a magnetized plasma

MHD

$$\frac{\partial \mathbf{B}}{\partial t} = \mathbf{curl}\,(\mathbf{u} \times \mathbf{B}) + \eta \nabla^2 \mathbf{B}, \quad \eta = 1/\mu_0 \sigma$$

Source (/sink) Non-linear

Sink linear (if kinetic σ)

Diffusion ***u*** = 0

Object	$\eta[\mathrm{m}^2/\mathrm{s}]$	$L[\mathrm{m}]$	$U[\mathrm{m/s}]$	R_{m}	P_{m}	τ_{d}
Earth (outer core)	2	10^6	10^{-3}	300	10^{-}	10^4 years
Sun (molecular)	1	10^8	100	10^{10}	10^{-}	10^9 years
Sun (turbulent)	10^8	10^8	100	100	~ 1	3 years
lab experiment	0.1	1	10	100	10^{-}	10 s

Table 1: Typical values for the magnetic Reynolds number R_{m} and diffusion time scales for the core of the Earth, the Sun and laboratory liquid sodium experiments

Ideal MHD, η = 0

Expanding the expression of the right hand side of the ideal induction equation Eq. (22) leads to

Stretch shear compress

$$\frac{\partial \boldsymbol{B}}{\partial t} = -(\boldsymbol{v} \cdot \boldsymbol{\nabla})\boldsymbol{B} + (\boldsymbol{B} \cdot \boldsymbol{\nabla})\boldsymbol{v} - \boldsymbol{B}\,(\boldsymbol{\nabla} \cdot \boldsymbol{v})\,. \tag{23}$$

Dynamo (epoch 2021) in a nutshell

- MHD is sufficient (Parker)
- Ingredients:
- Broken symmetry (Cowling 1930s "anti-dynamo theorem")
- Rotation → symmetry breaking [Coriolis force $\Omega \times \mathbf{u}$ is a pseudo vector]
- ``Ω-effect'' (a)-(c) differential rotation
- ``Ω-effect'' (a)-(c) differential rotation
- u_r (convection) => u_ϕ and u_θ cyclonic "α-effect", + emergence of buoyant tubes and reconnection (d)-(f)
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- completes the ``cycle'':
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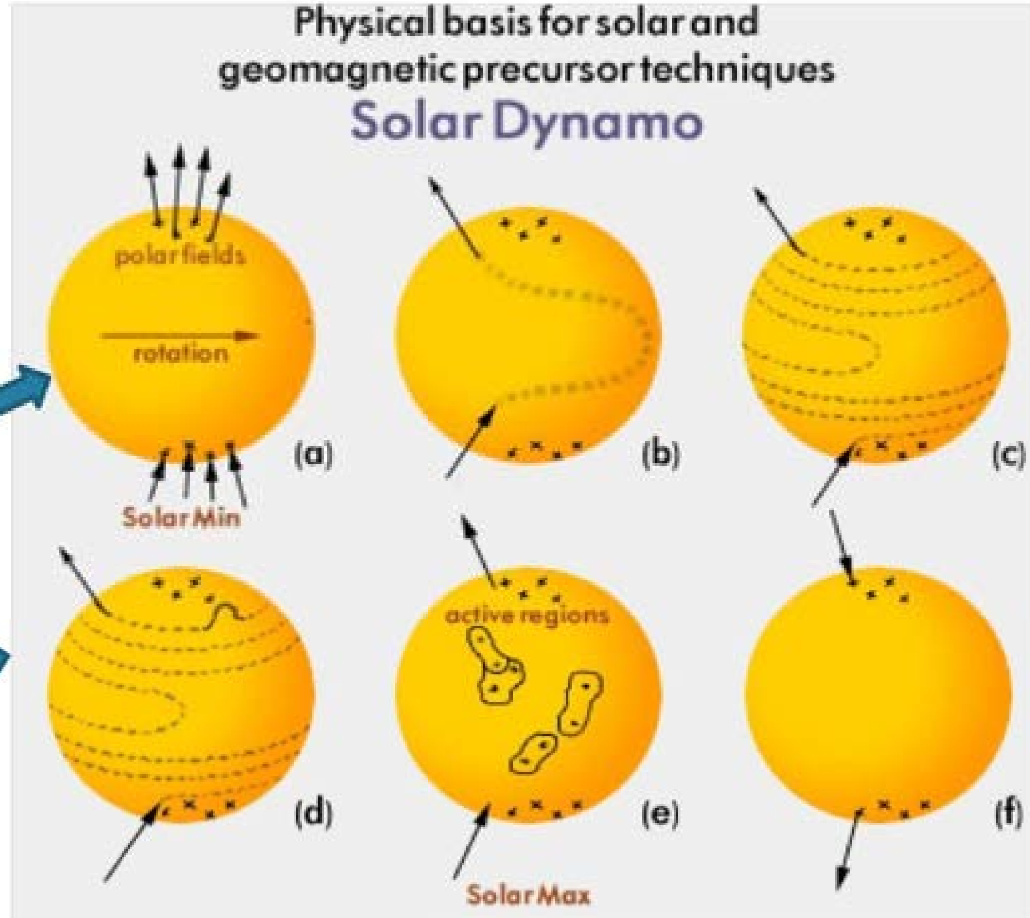
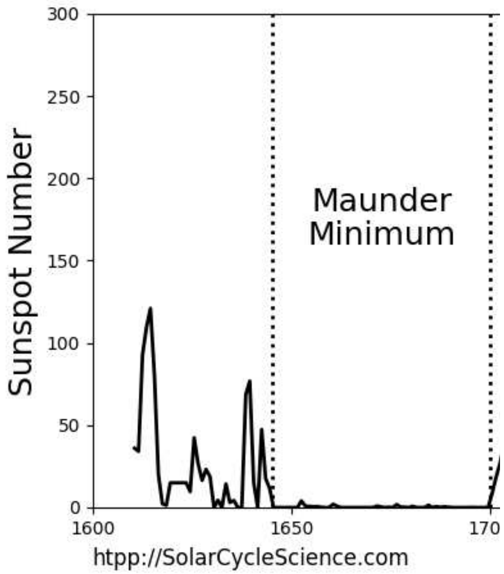


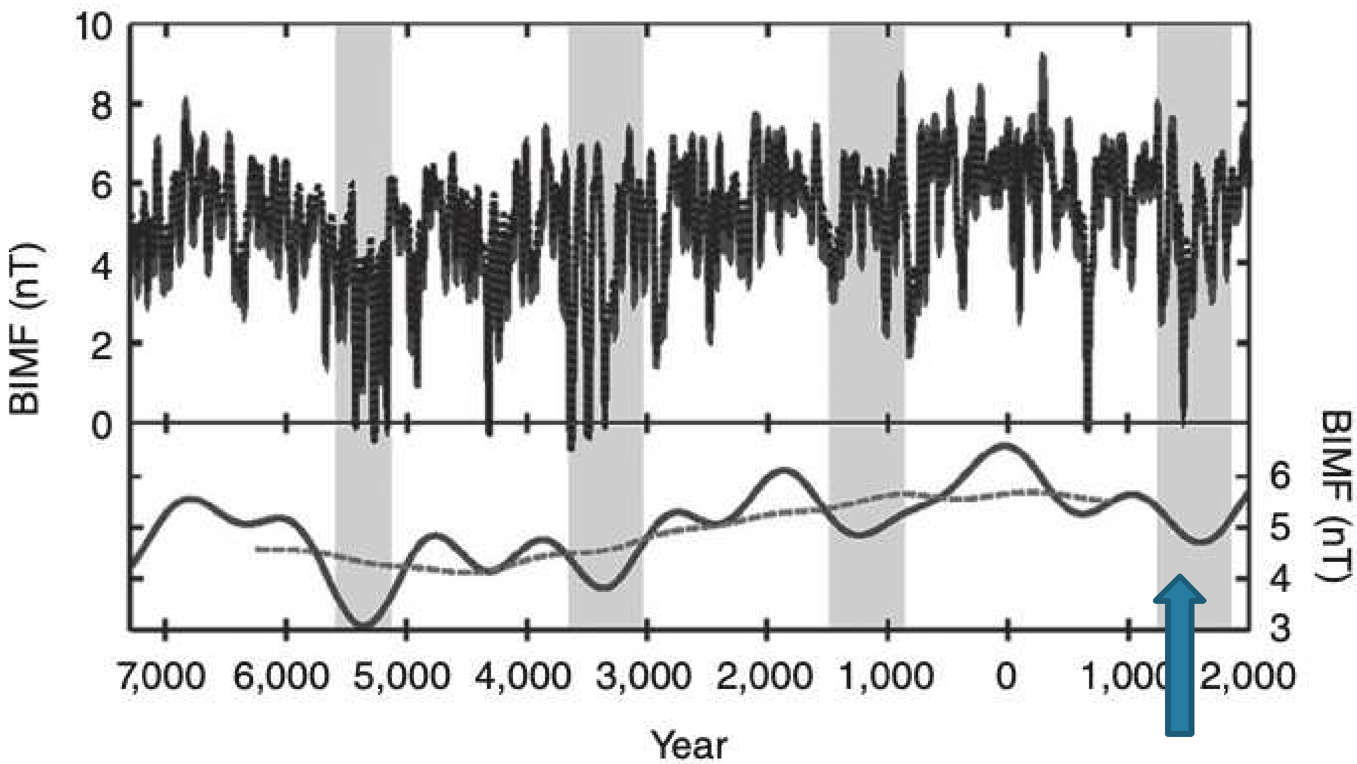
$\Omega \quad \alpha \quad \Omega \quad \alpha \ldots$

so that $B_\phi \rightarrow B_\theta \rightarrow B_\phi \rightarrow B_\theta \rightarrow$

end of physics interlude

The magnetized Sun in time: solar system data





past 400 years

25. The solar magnetic field near the Earth is shown, estimated from analysis of Galactic cosmic rays as imprinted in geological records spanning years 7300 BCE–2000 AD. The units along the *y*-axis are nano-Tesla (10^{-9} Tesla). The upper panel shows raw data, the lower shows data smoothed to reveal trends over ≈1,000 years (solid line) and longer (dashed line). Shaded areas are epochs of extended minima. The Maunder Minimum is seen as the rightmost point reaching zero in the upper plot, eight earlier such episodes are also visible.

holocene
past 9300 years

For solar variations on astronomical timescales we must rely on Stellar data

Angular momenta, magnetism and activity

- Stars are endowed with non-zero angular momentum **J**

- Sun-like stars have convection, differential rotation
  => dynamos => ejection of matter with angular momentum
  => d**J/**dt is –ve

- ``Spin-down'', age-rotation elations, rotation-activity relations (next slide)

- Now- Kepler, Tess.. astero-seismology photometry in space
  - Vastly improved stellar ages and rotation rates (periods of rotation)
  - **"Gyro-chronology"**

chromospheric (= magnetic) activity vs rotation and convection (Noyes et al 1984)

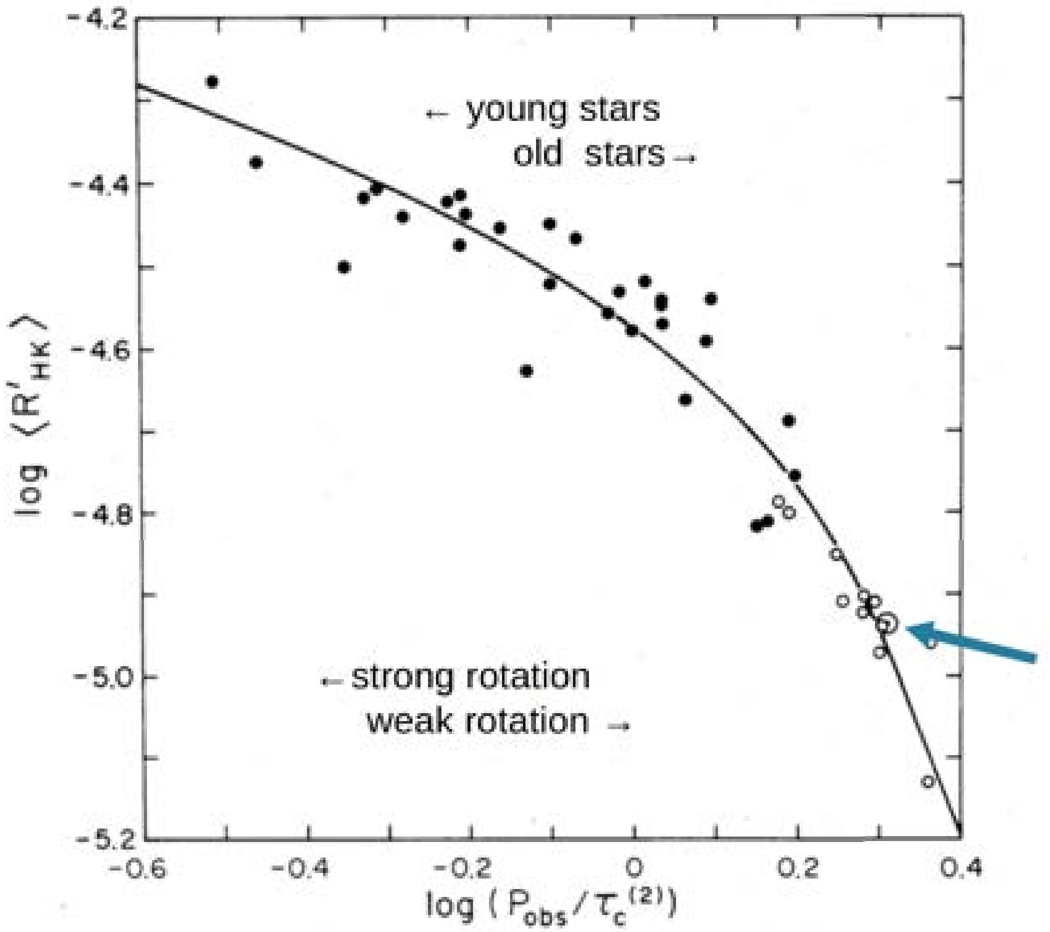
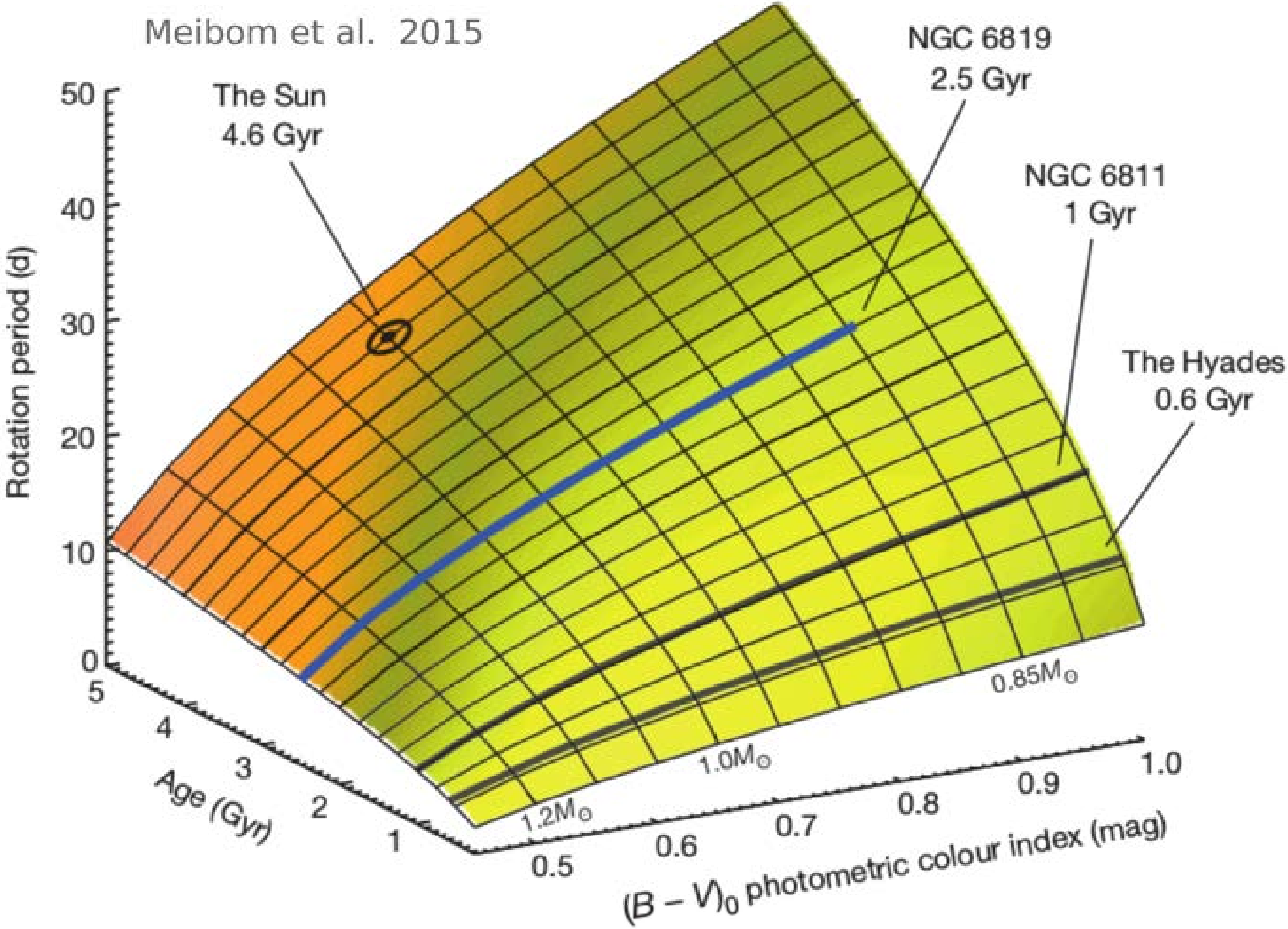


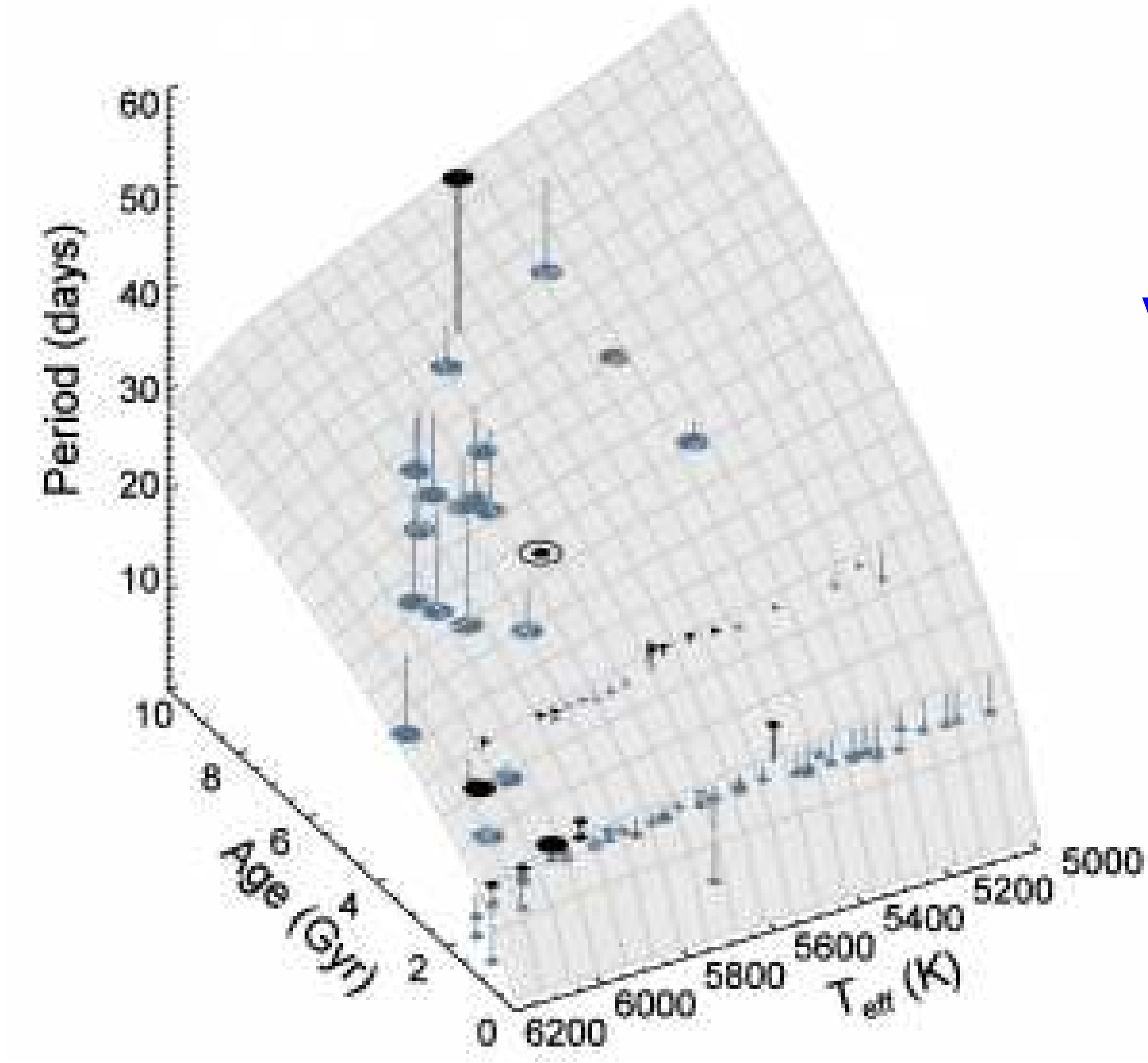
FIG. 8.—$\langle R'_{HK} \rangle$ plotted vs. $P_{obs}/\tau_c^{(2)}$, where $\tau_c^{(2)}$ is given by eq. (4). Solid line is eq. (3).

x-axis = ``Rossby number''= rotation period/convection turnover

Sun fits stellar trends

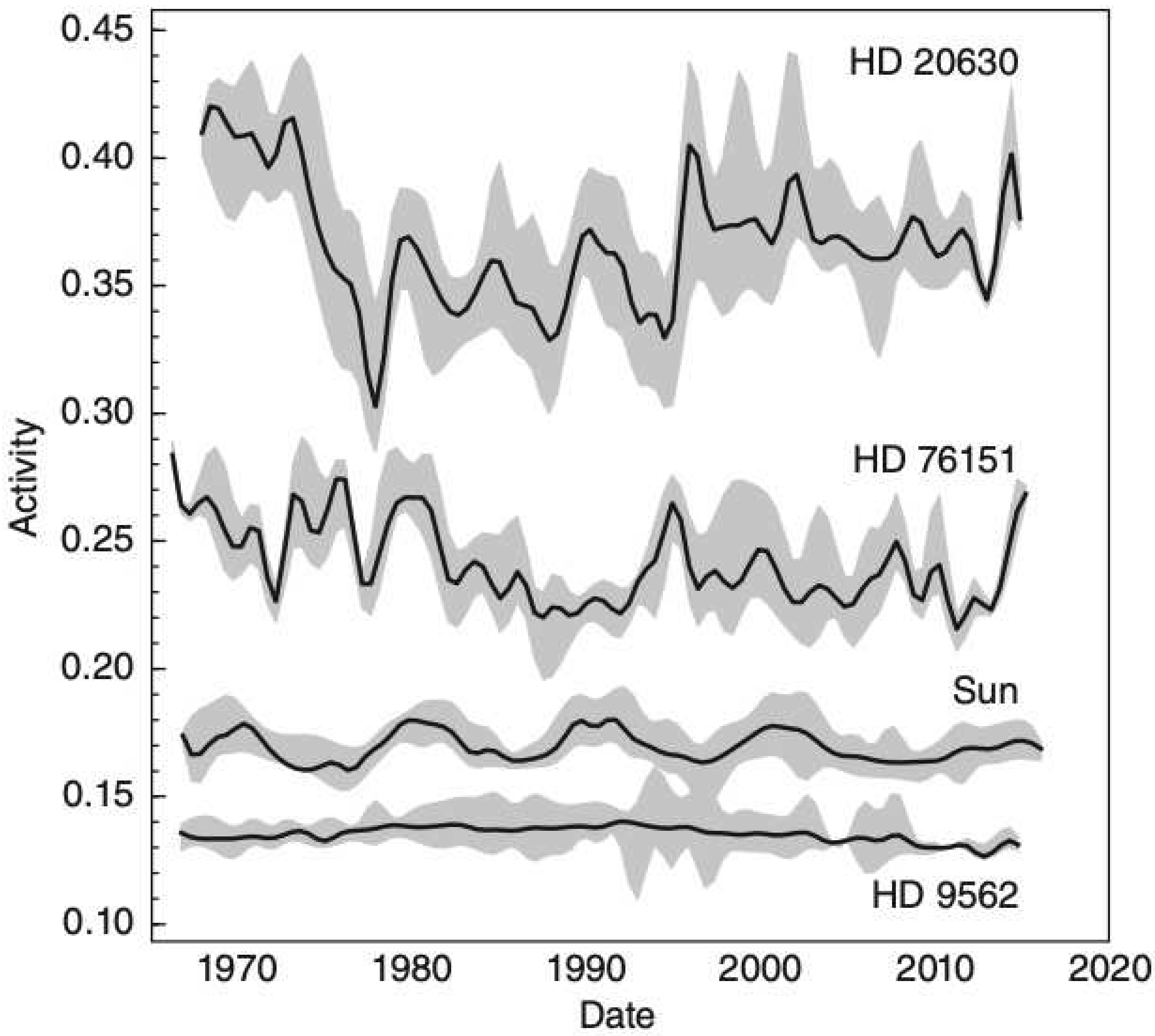
statistical "order from chaos"


Meibom et al. 2015
Rotation period (d)
50
40
30
20
10
0
The Sun
4.6 Gyr
NGC 6819
2.5 Gyr
NGC 6811
1 Gyr
The Hyades
0.6 Gyr
0.85M⊙
1.0M⊙
1.2M⊙
5
4
3
2
1
Age (Gyr)
0.5
0.6
0.7
0.8
0.9
1.0
(B – V)0 photometric colour index (mag)



- “Gyro-chronology”

van Saders et al 2016



Egeland 2019

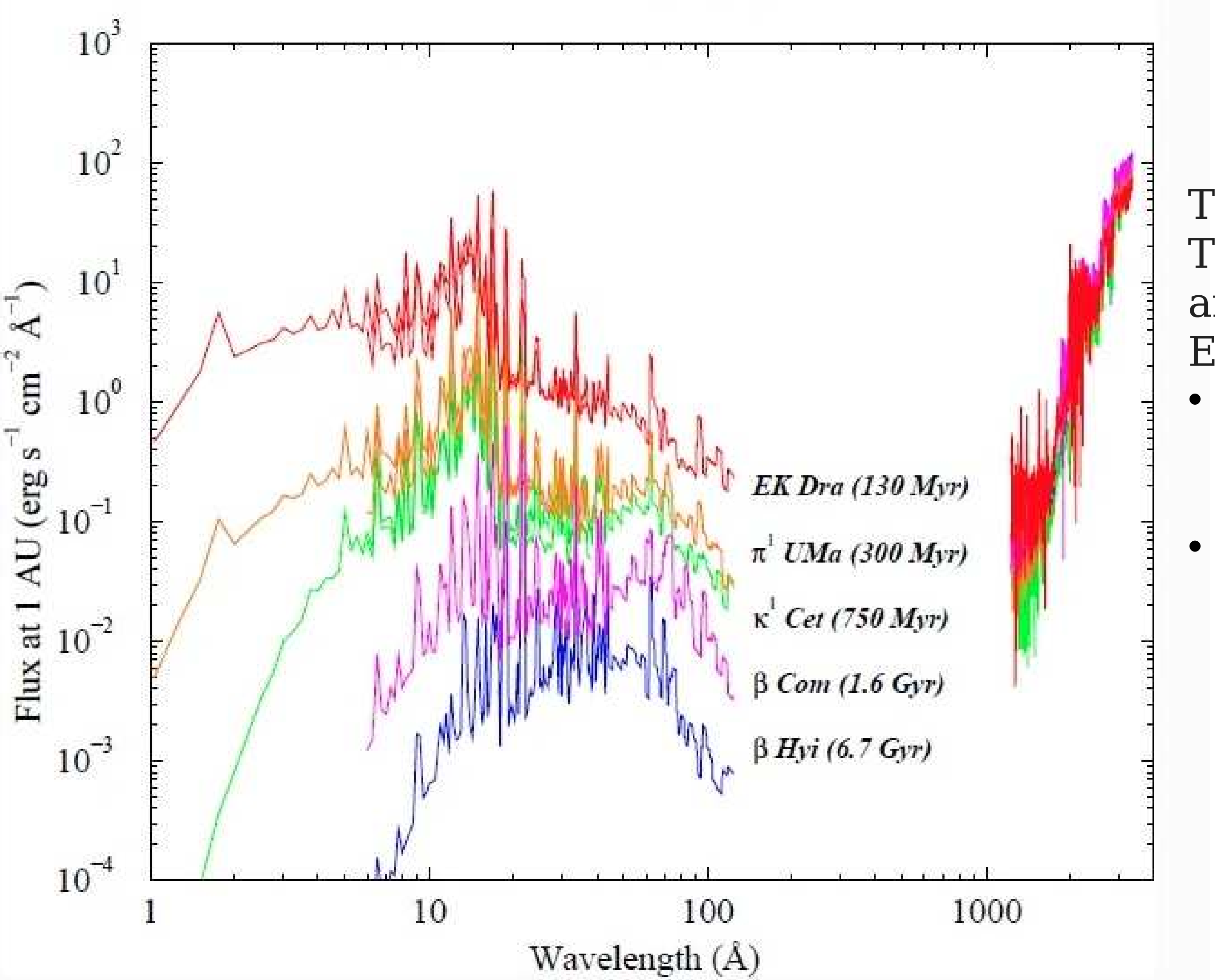
Sun-like stars

sun: cycles

stars: 30% cycle

Young sun

Young sun

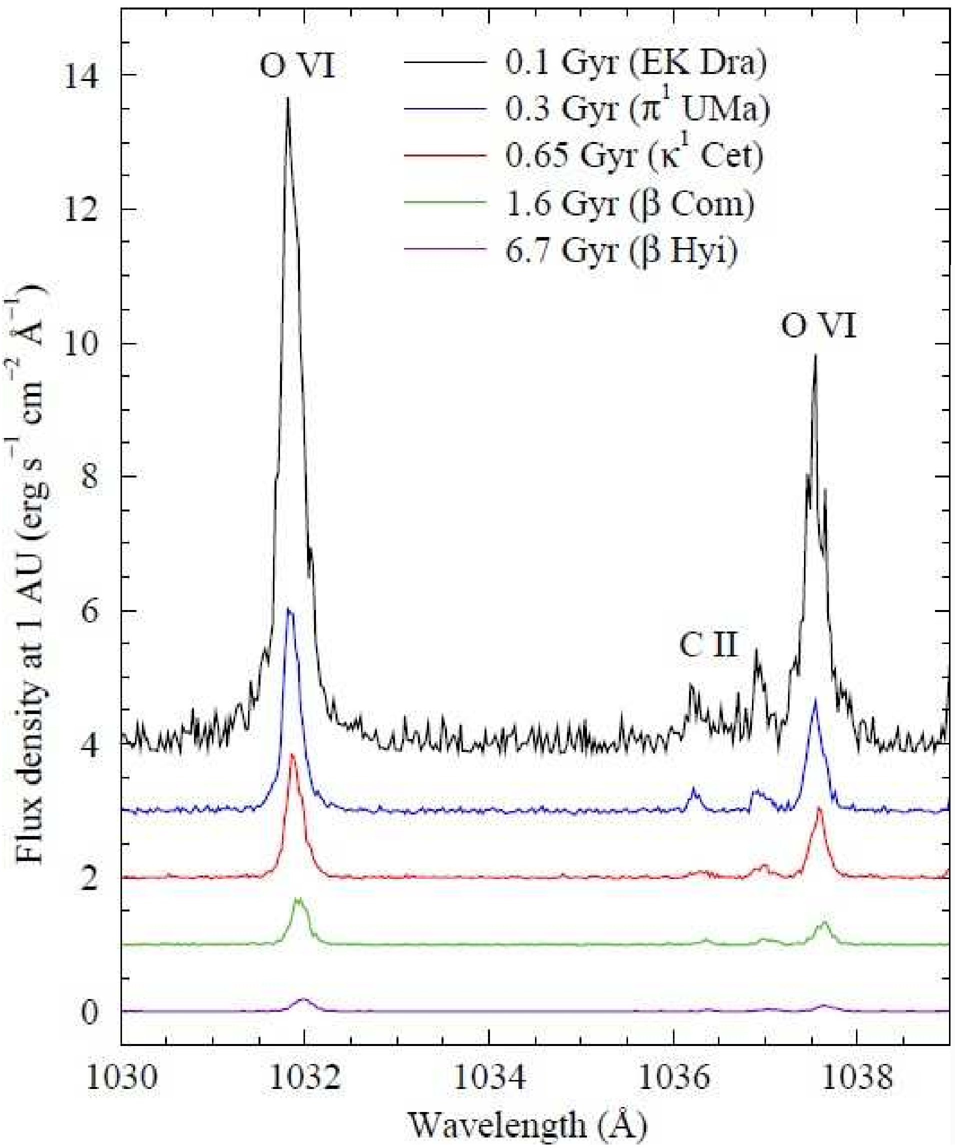


The Sun in Time: Activity and Environment

- Manuel Güdel

- 2007 LRSP

Young sun



The Sun in Time: Activity and Environment

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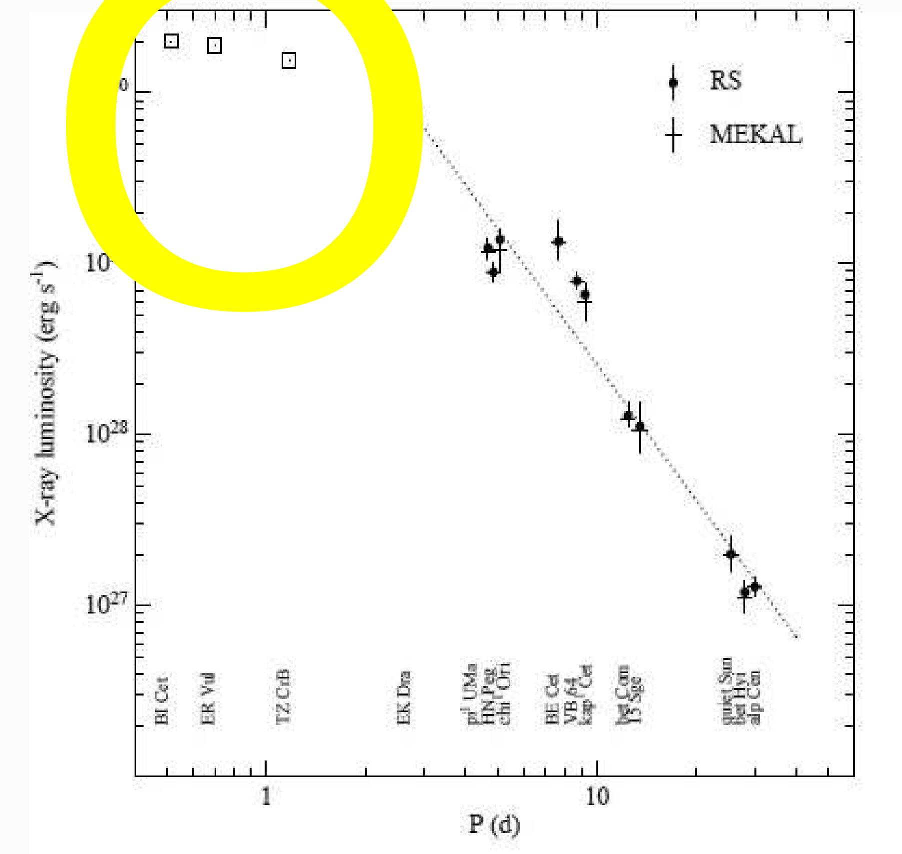
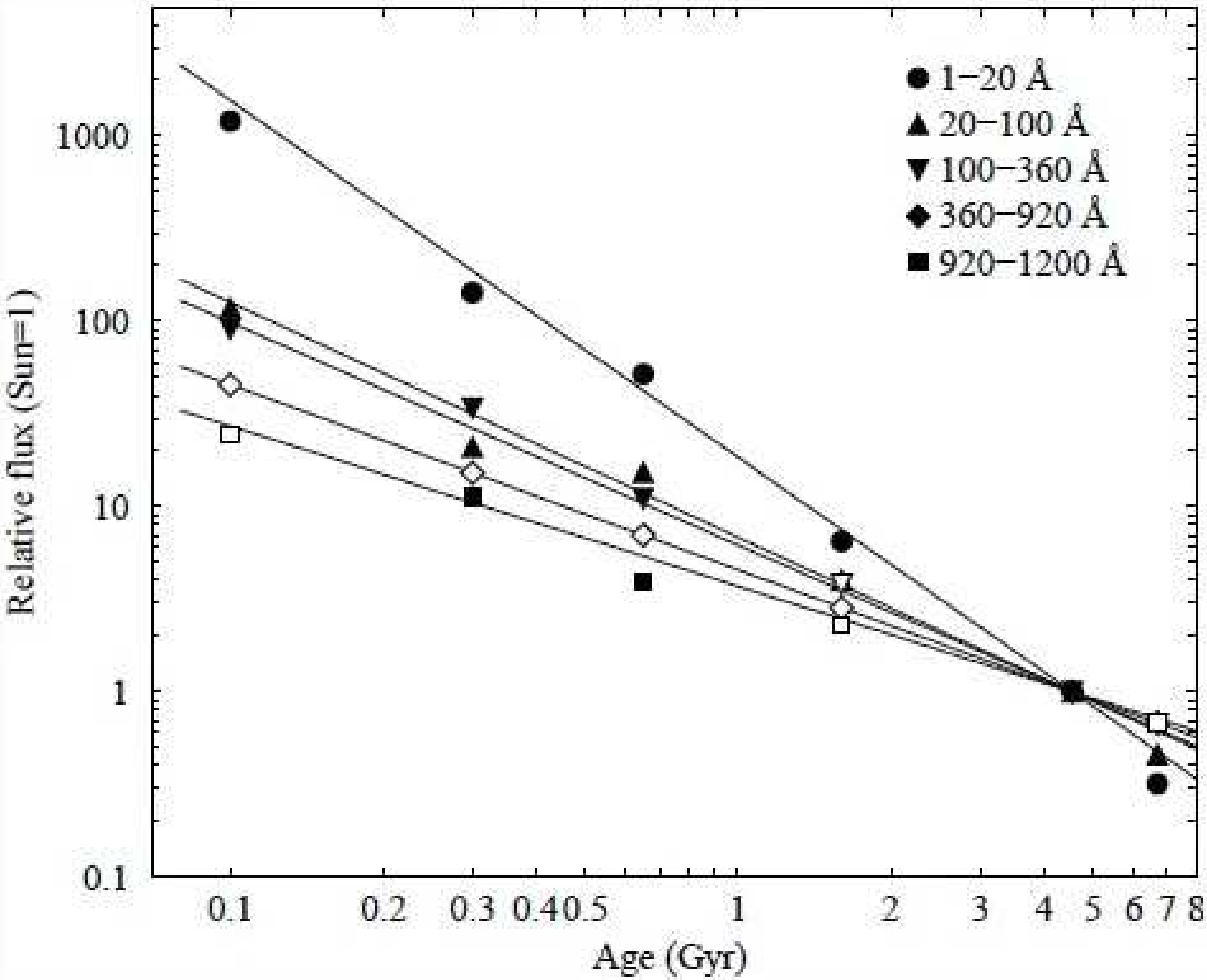


Young sun



The Sun in Time: Activity and Environment

- Manuel Güdel
- 2007 LRSP
- Logarithmic scale!

Young Sun & planets

Astron Astrophys Rev (2018) 26:2
https://doi.org/10.1007/s00159-018-0108-y

CrossMark

REVIEW ARTICLE

Origin and evolution of the atmospheres of early Venus, Earth and Mars

Helmut Lammer[1] · Aubrey L. Zerkle[2] · Stefanie Gebauer[3] · Nicola Tosi[4,5] · Lena Noack[6] · Manuel Scherf[1] · Elke Pilat-Lohinger[7] · Manuel Güdel[7] · John Lee Grenfell[3] · Mareike Godolt[5] · Athanasia Nikolaou[4,5]

Received: 16 March 2017 / Published online: 10 May 2018

Abstract We review the origin and evolution of the atmospheres of Earth, Venus and Mars from the time when their accreting bodies were released from the protoplanetary disk a few million years after the origin of the Sun. If the accreting planetary cores

Young Sun & planets

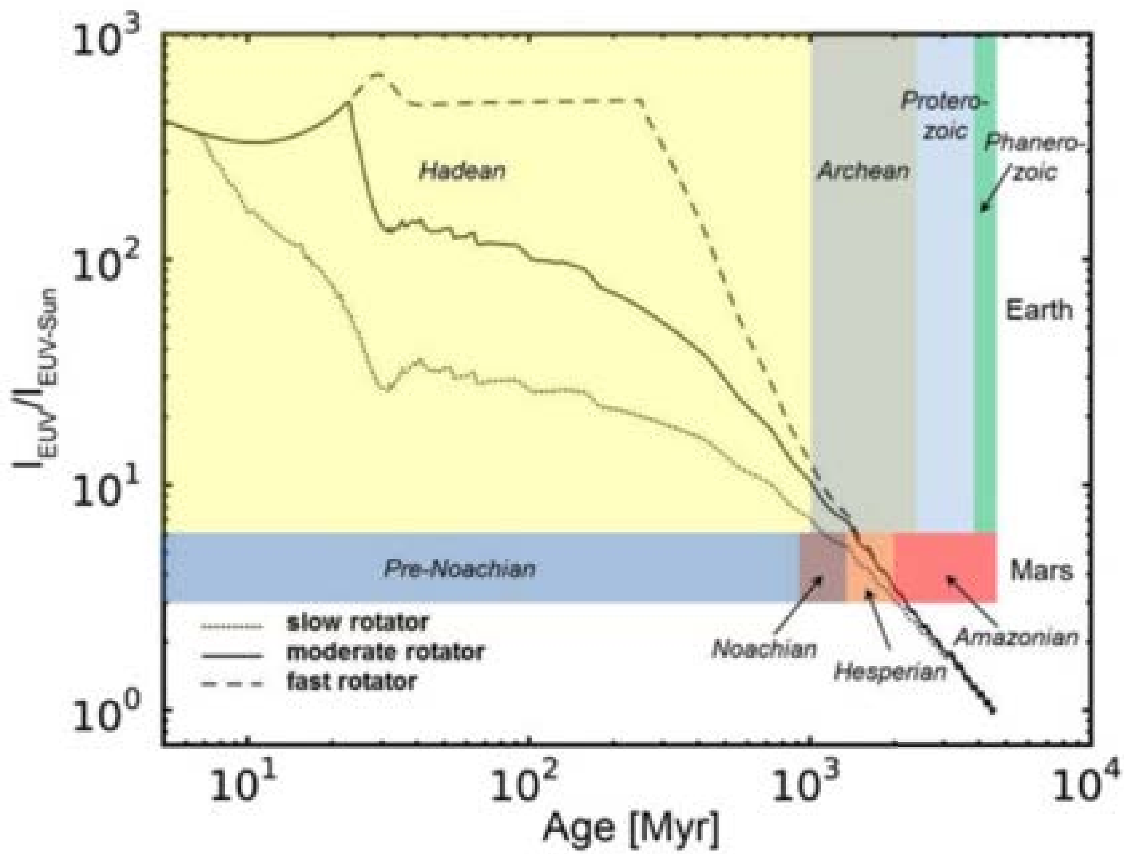
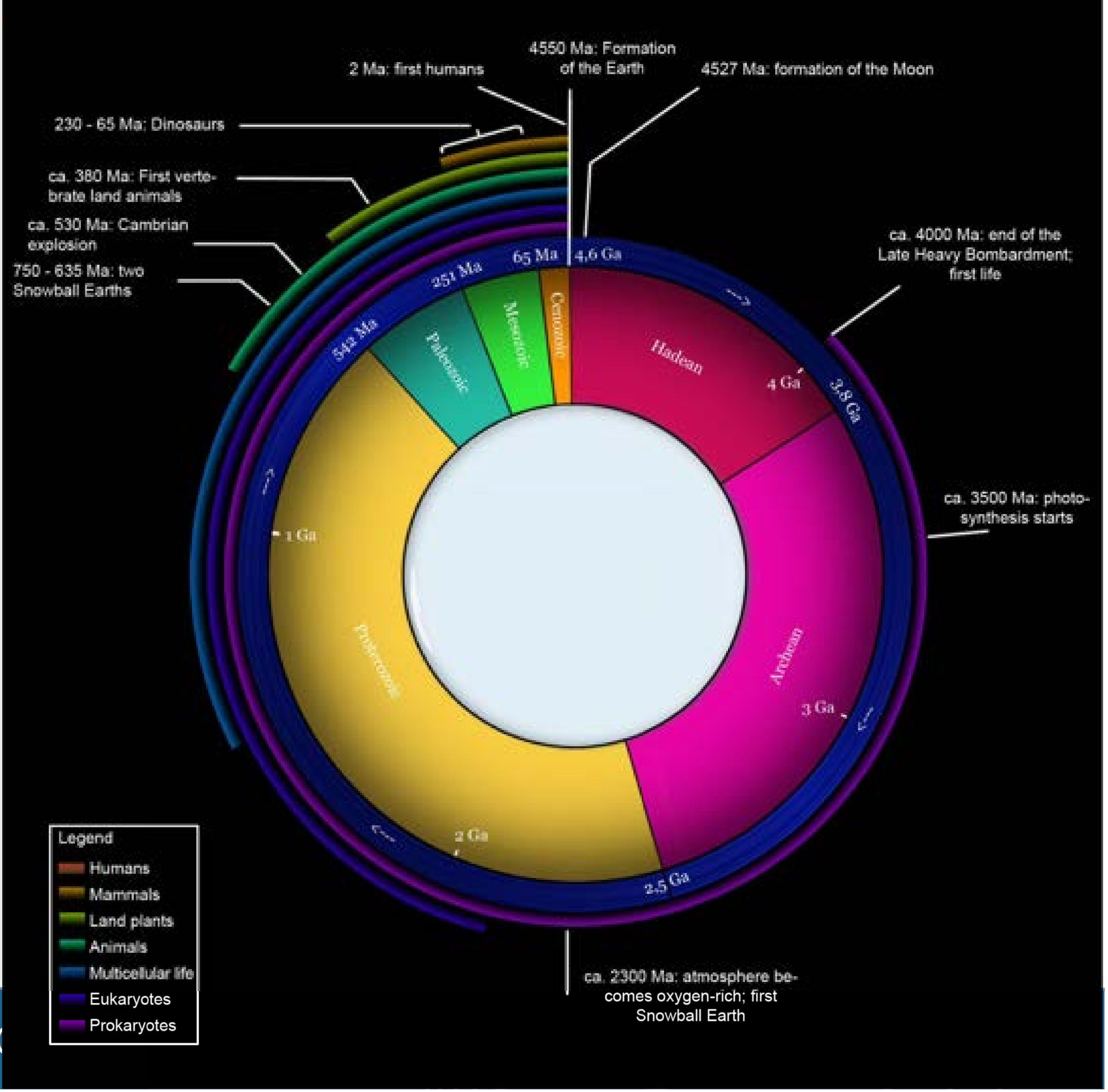
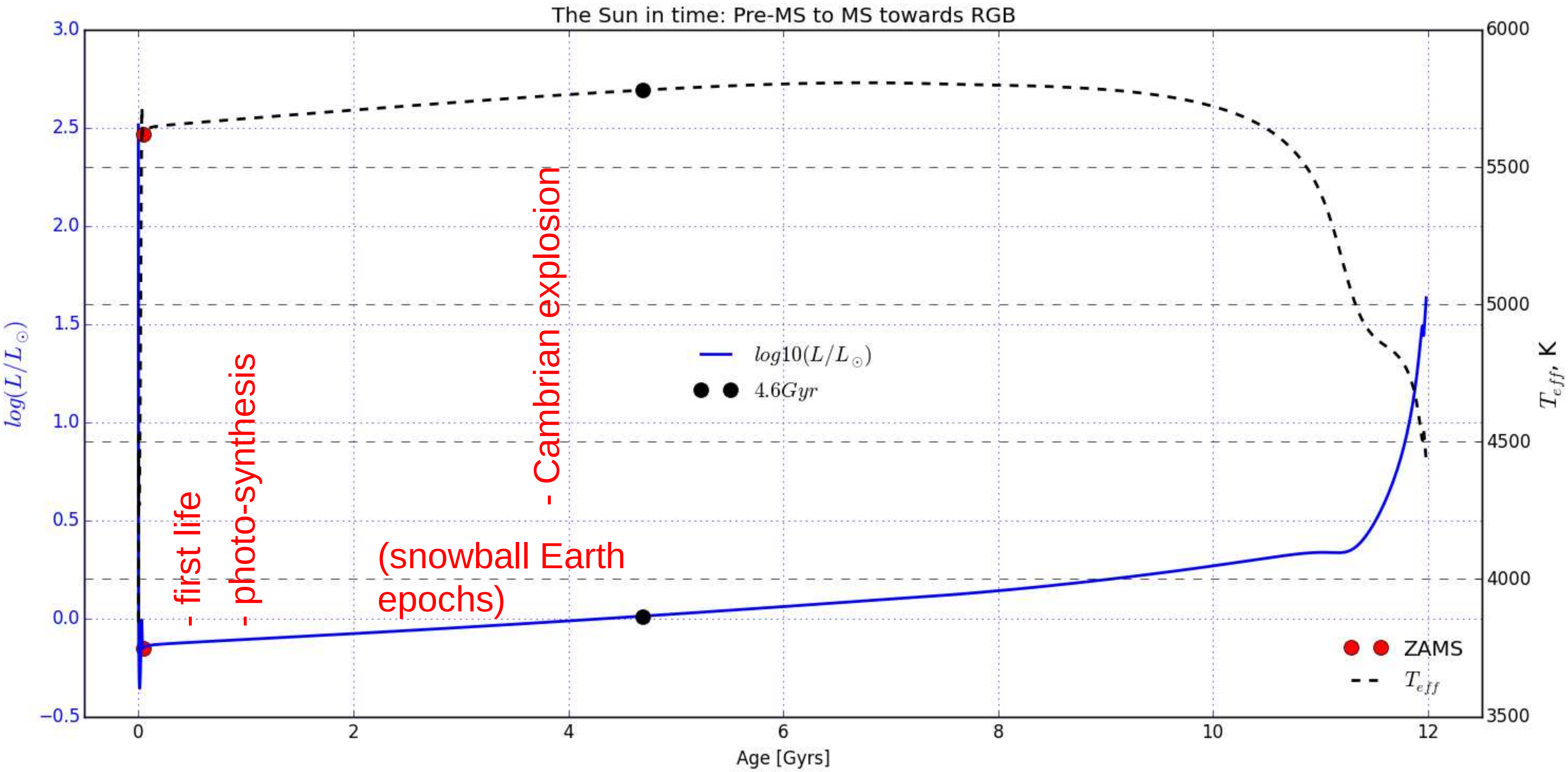


Fig. 1 Expected rotation-based EUV enhancement factor normalized to that of today's solar level (after Tu et al. 2015). The dotted line corresponds to the EUV activity evolution enhancement of slowly rotating weakly active young solar-like stars. The solid line corresponds to a young Sun rotating moderately, while the dashed line represents the evolution of a fast rotating EUV active young solar-like star. The shaded areas mark the different geological eons on Earth and Mars

back on Earth



stellar and terrestrial context



→ no more magnetic spin-down (van Saders+, KEPLER asteroseismology gyro-chronology)

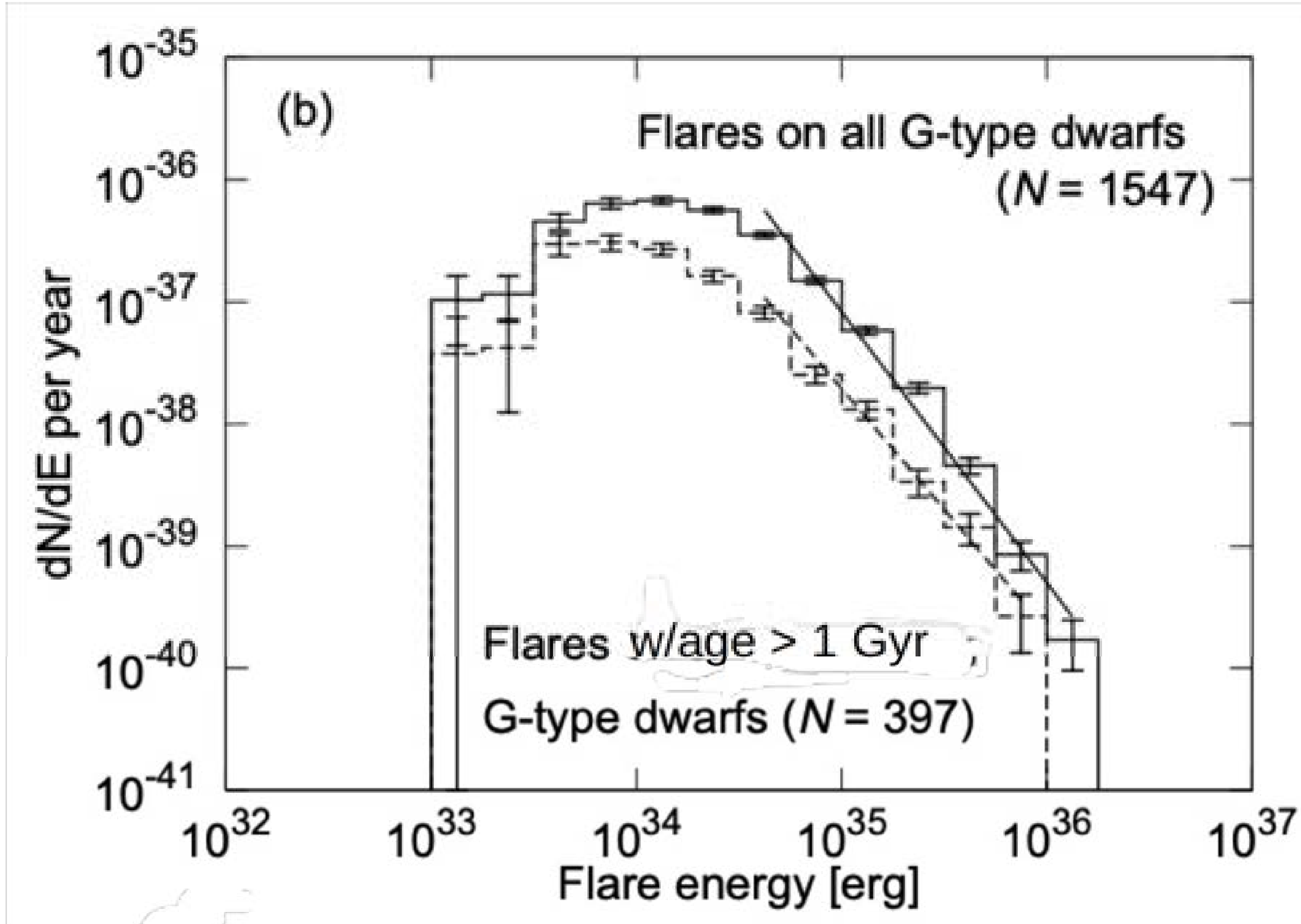
Kepler and flares on Sun-like stars

Solar flare < 5 ·10^{32} erg

superflares < 10^{36} erg

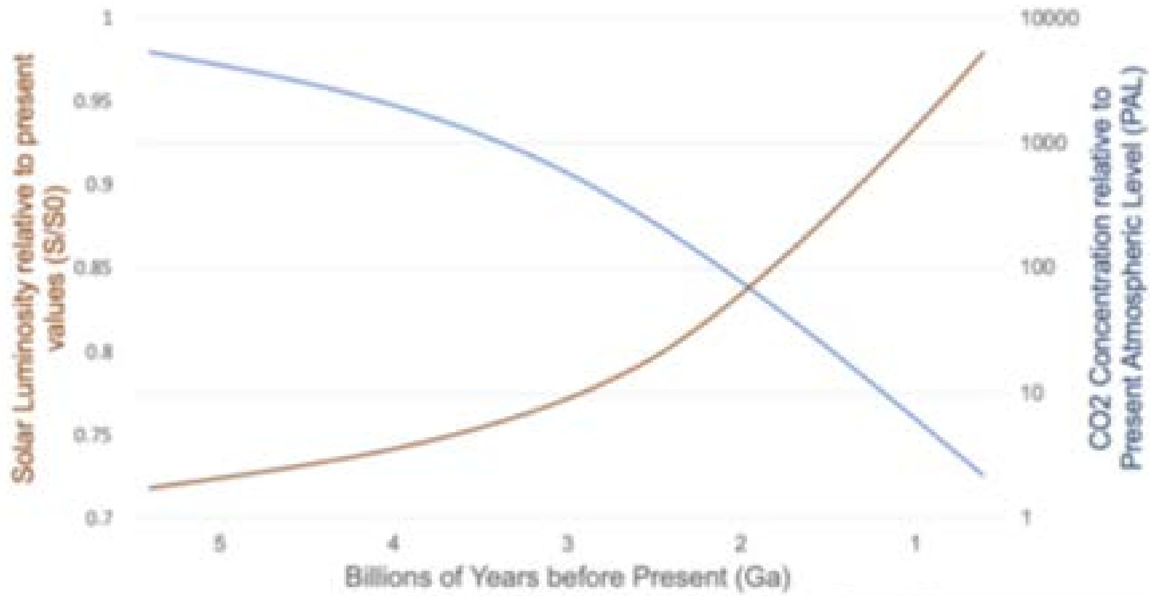
a [Kepler] superflare occurs on a GV star once every 440 yr

Shibayama et al. 2013



- a superflare could have profound effects on the habitability of any planets that might orbit the star.

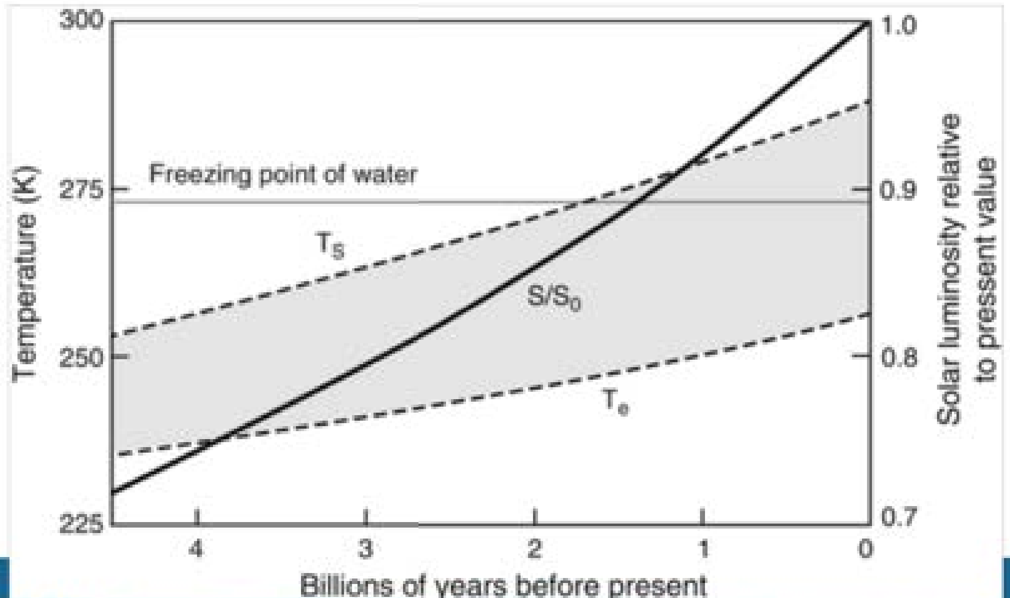
Faint young Sun and Earth's atmosphere



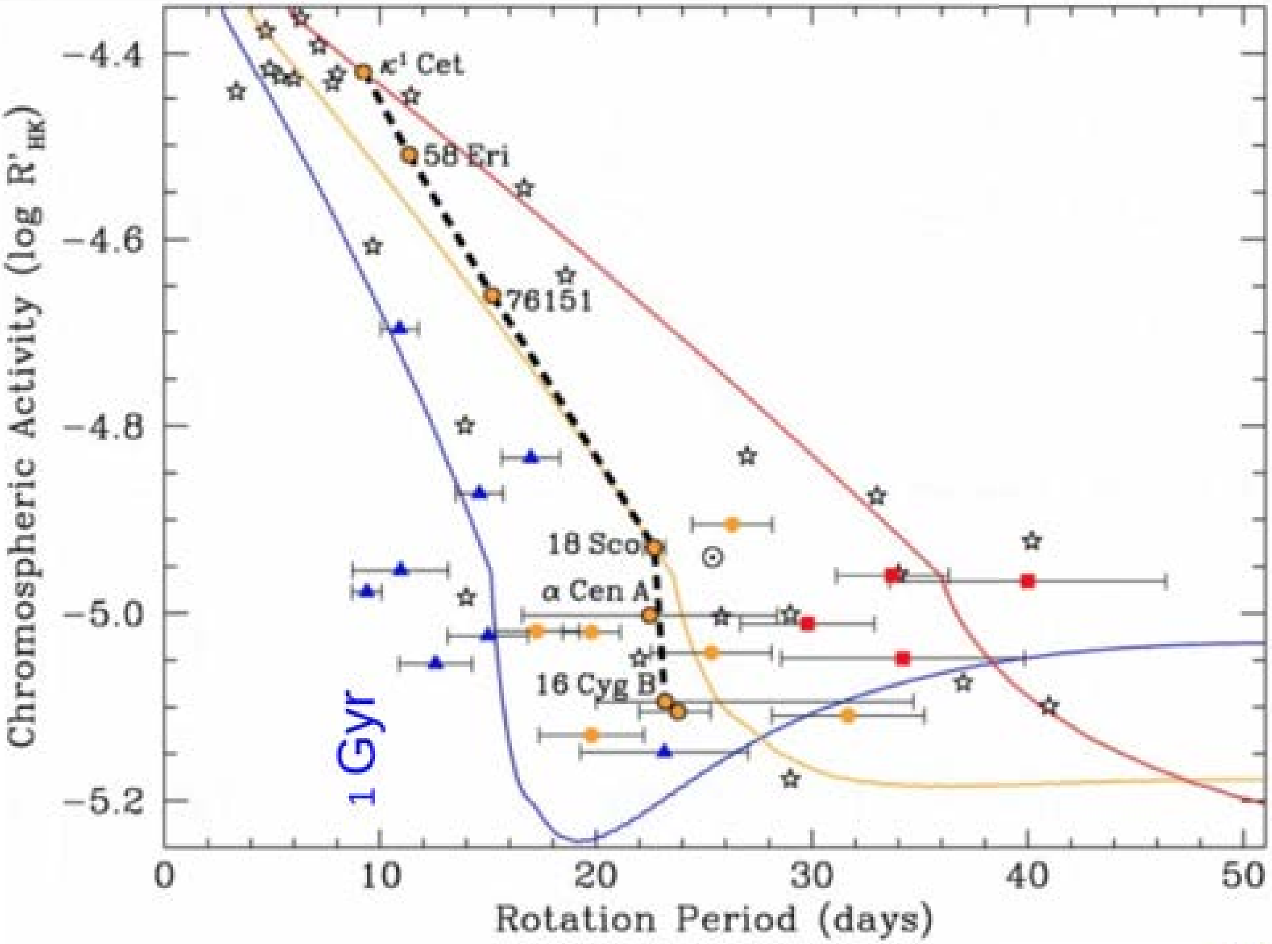
"faint young Sun ~~paradox~~"

~~astronomical (e.g. mass loss)~~

terrestrial



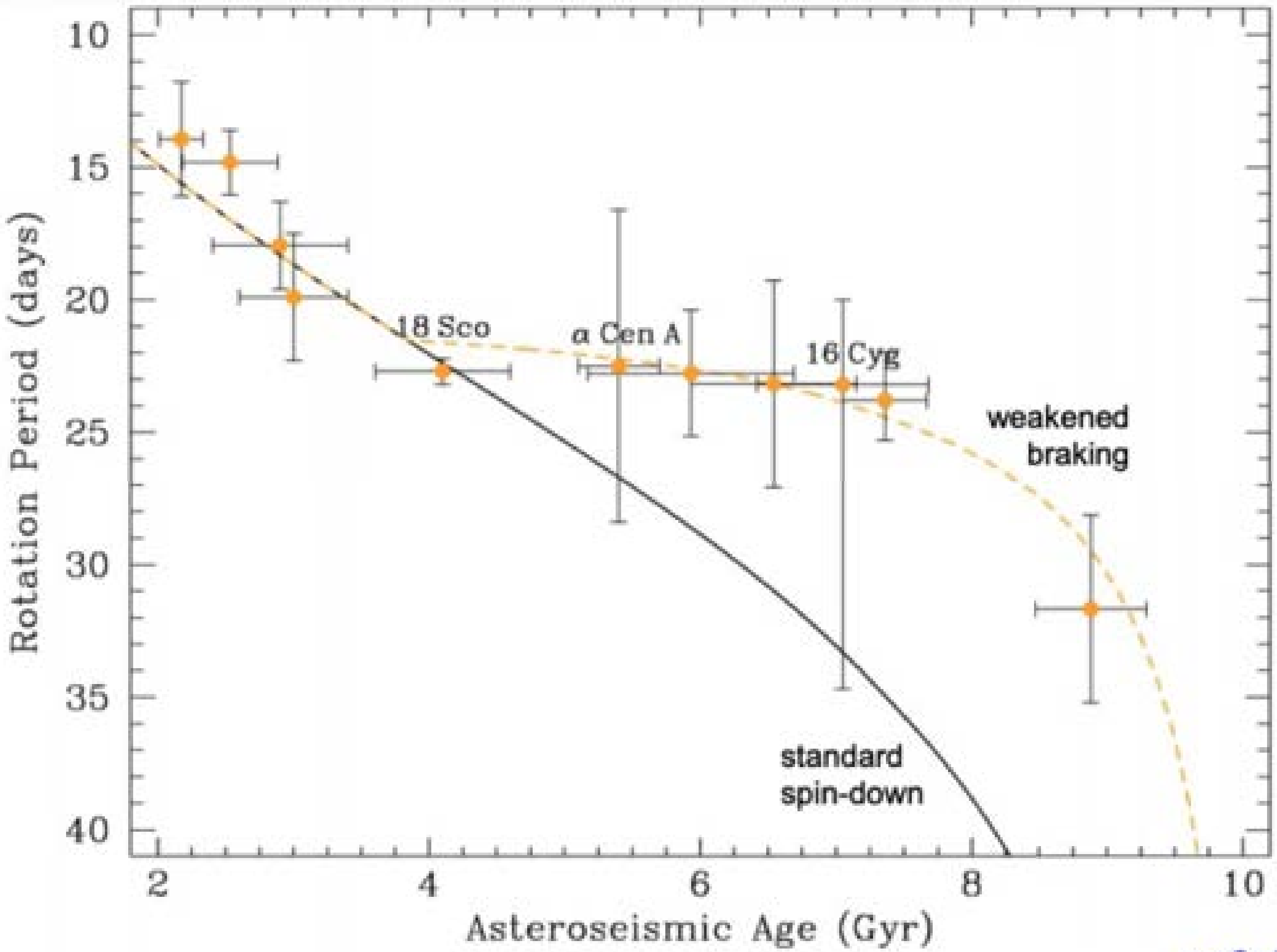
Rotation and activity decouple



Metcalfe+ (2016)

Old Sun

Spin-down stalls near solar age



van Saders+ (2016)

X rays, coronae – Schmitt 1997

Coronae on solar-like stars

Jürgen H.M.M. Schmitt

Max-Planck-Institut für Extraterrestrische Physik, Postfach 1603, D-8

Received 14 March 1996 / Accepted 27 June 1996

Abstract. The results of a complete and sensitive X-ray survey of all known stars of spectral type A, F, and G in the immediate solar vicinity with distances less than 13 pc are presented. The

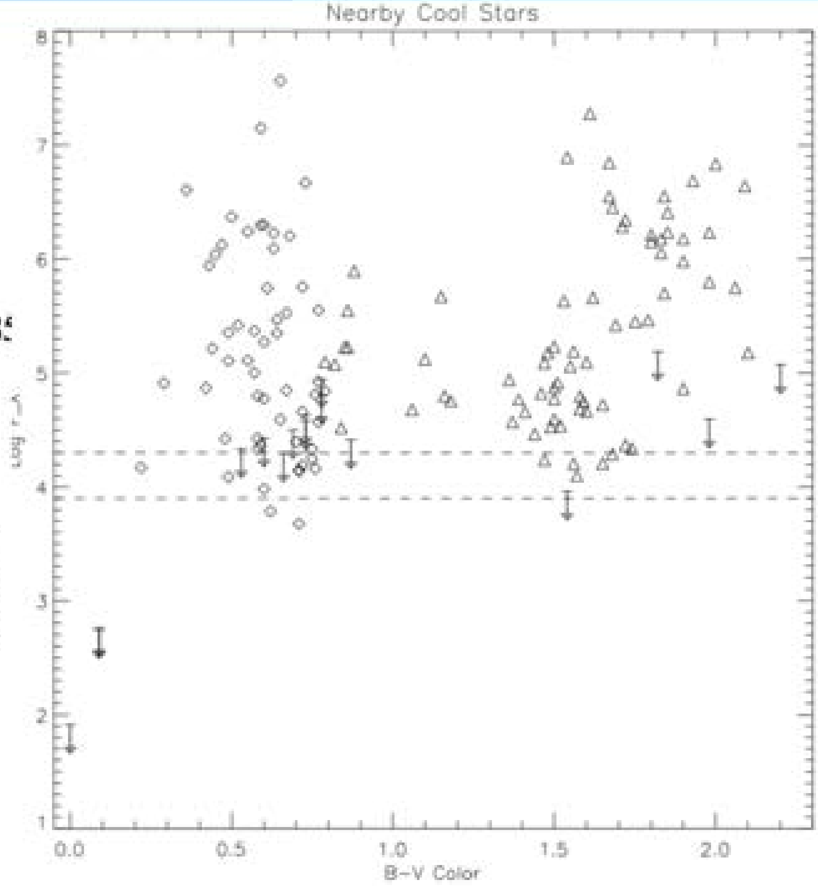


Fig. 8. Mean X-ray surface brightness F_X vs. $B-V$ color for my sample stars (including A-type stars drawn as upper limits). F and G stype stars are plotted with diamonds, K and M type stars (as discussed by Schmitt et al. 1995) with upward triangles. For comparison the typical X-ray surface flux level (in the PSPC band pass) from solar coronal holes is shown by the two dashed curves. Clearly the observed solar coronal hole surface flux provides a good description of the observed stellar minimum X-ray flux. See text for details.

X rays in convecting stars are universal.

X-ray surface flux densities do not drop below 10^4 erg cm^{-2}s^{-1}.

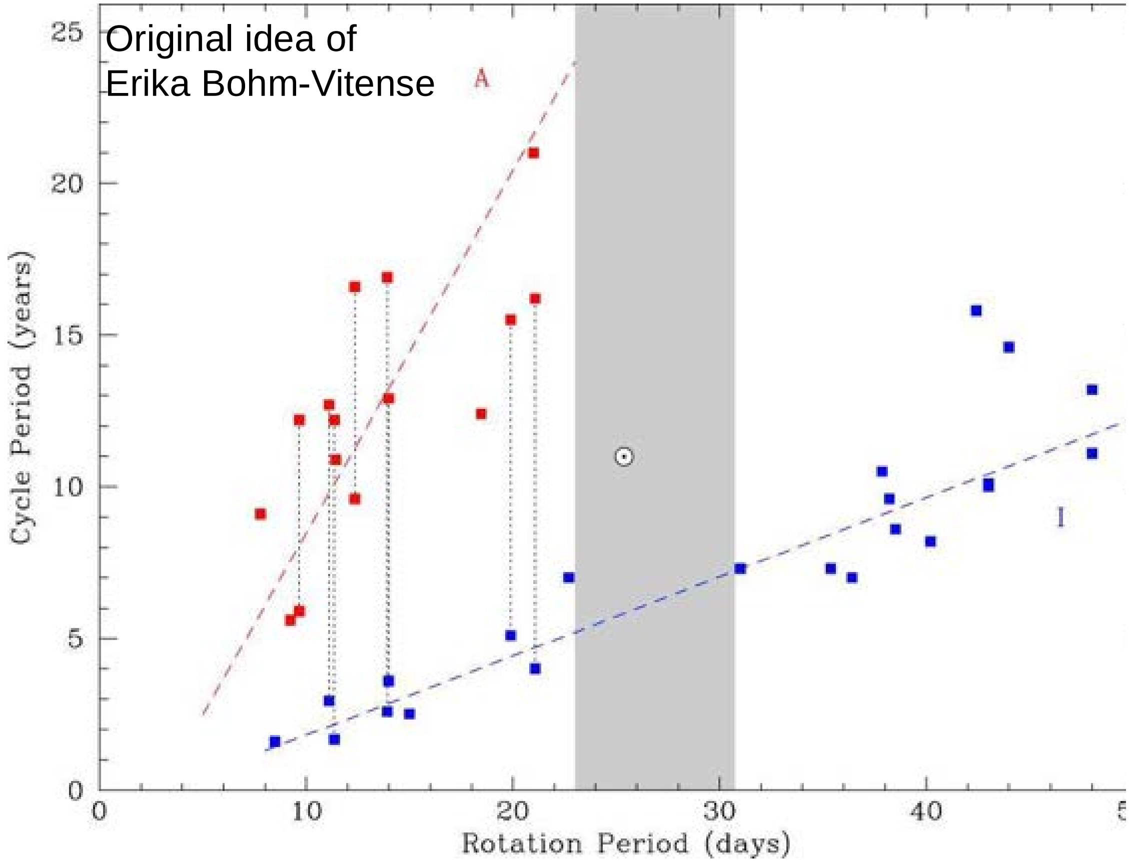
stellar context
is the Sun an Oddball?

1. Always remember we only see it equator-on (tilt= 7°)

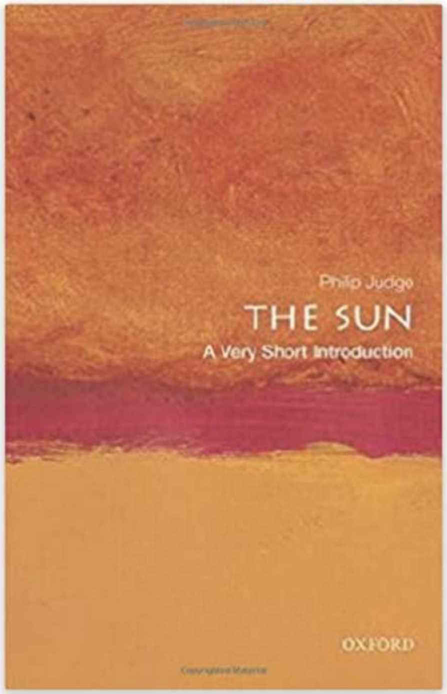
2. It possesses the most regular star-spot ***cycle*** of all stars, similar to K not G stars (Egeland 2017 PhD thesis+)

3. Photometry seems less variable (Radick + 2018, others) for its age and amount of star-spot activity, happens to be at a crossover point. See also Reinhold et al 2020 *Science* **368** (6490), 518-521 -

4. Metcalfe et al 2016+, "THE SOLAR DYNAMO MAY BE IN TRANSITION", ApJL. (age > 4.5 Gyr ✸ loses dipolar field)



Look inside



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The Sun: A Very Short Introduction (Very Short Introductions) Paperback – July 1, 2020

by Philip Judge (Author)

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The Sun, as our nearest star, is of enormous importance for life on Earth - providing the warm radiation and light which allowed complex life to evolve. The Sun plays a key role in influencing our climate, whilst solar storms and high-energy events can threaten our communication infrastructure and satellites.

This *Very Short Introduction* explores what we know about the Sun, its physics, its structure, origins, and future evolution. Philip Judge explains some of the remaining puzzles about the Sun that still confound us, using elementary physics, and mathematical concepts. Why does the Sun form spots? Why does it flare? As he shows, these and other nagging difficulties relate to the Sun's continually variable magnetism, which converts an otherwise dull star into a machine for flooding interplanetary space with

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...The end

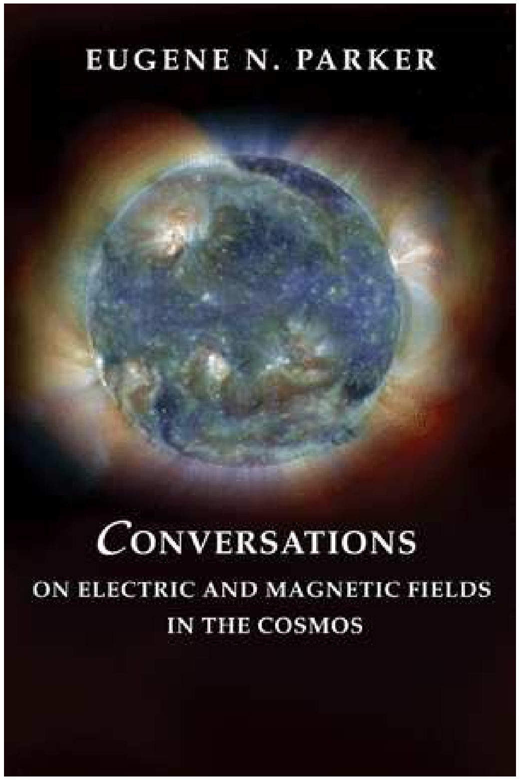
div B ≠ 0?
(abundant magnetic monopoles)

Monopoles

Free magnetic charges

No “M” in MHD

∴ Hydrodynamic universe



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for all astrophysics
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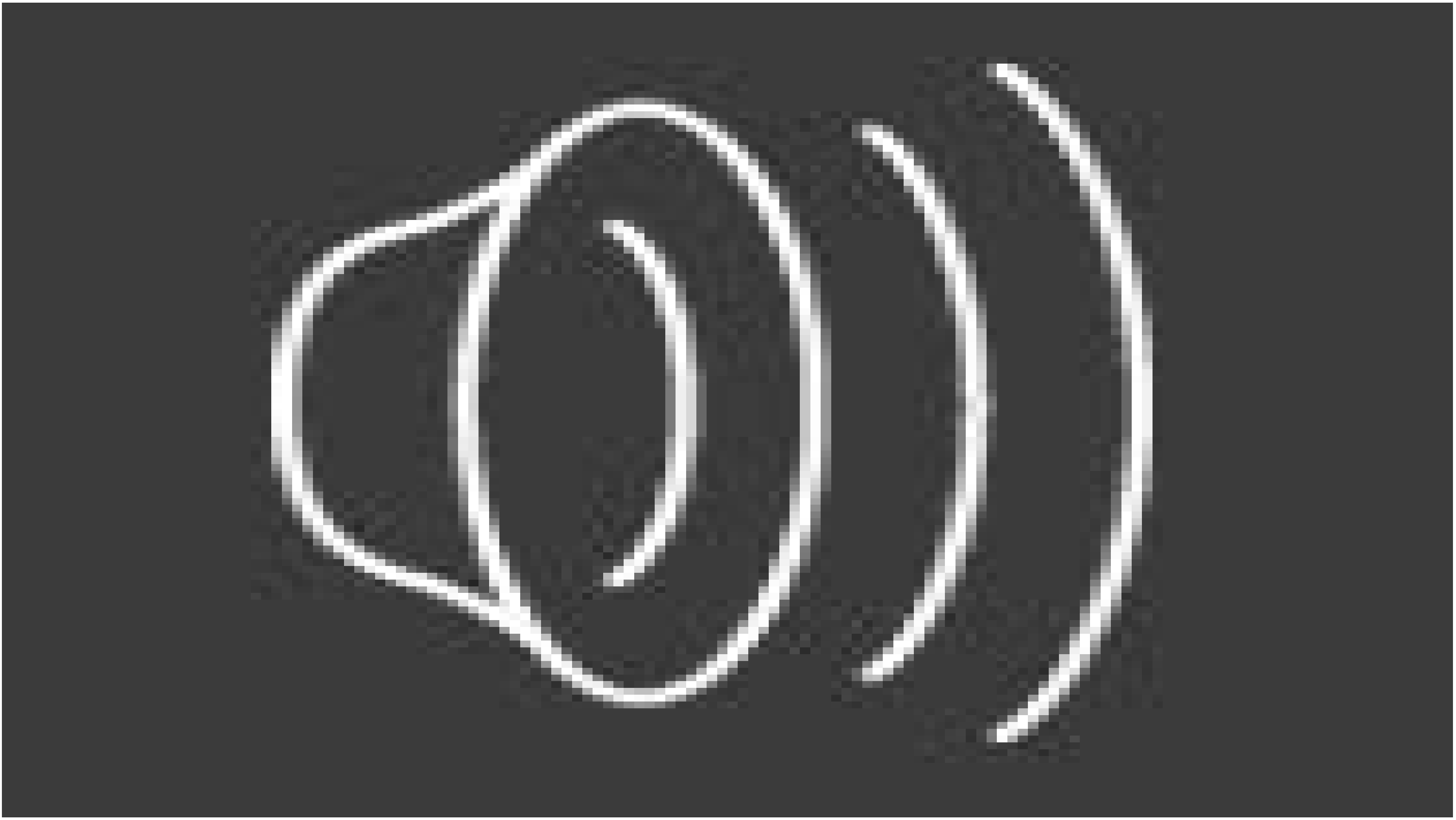

Olivier: "I came to you for answers. Very specific answers"
Gersonides: "So you keep telling me. And I will repeat the only answer I know. I have none. Not that I haven't spent the last forty years looking, but I find answers are as rare as golden eggs or unicorns. All I can do is help you look for yourself."

–Iain Pears, *The Dream of Scipio*

$$\frac{\partial \mathbf{B}_{\odot}}{\partial t} = ?$$