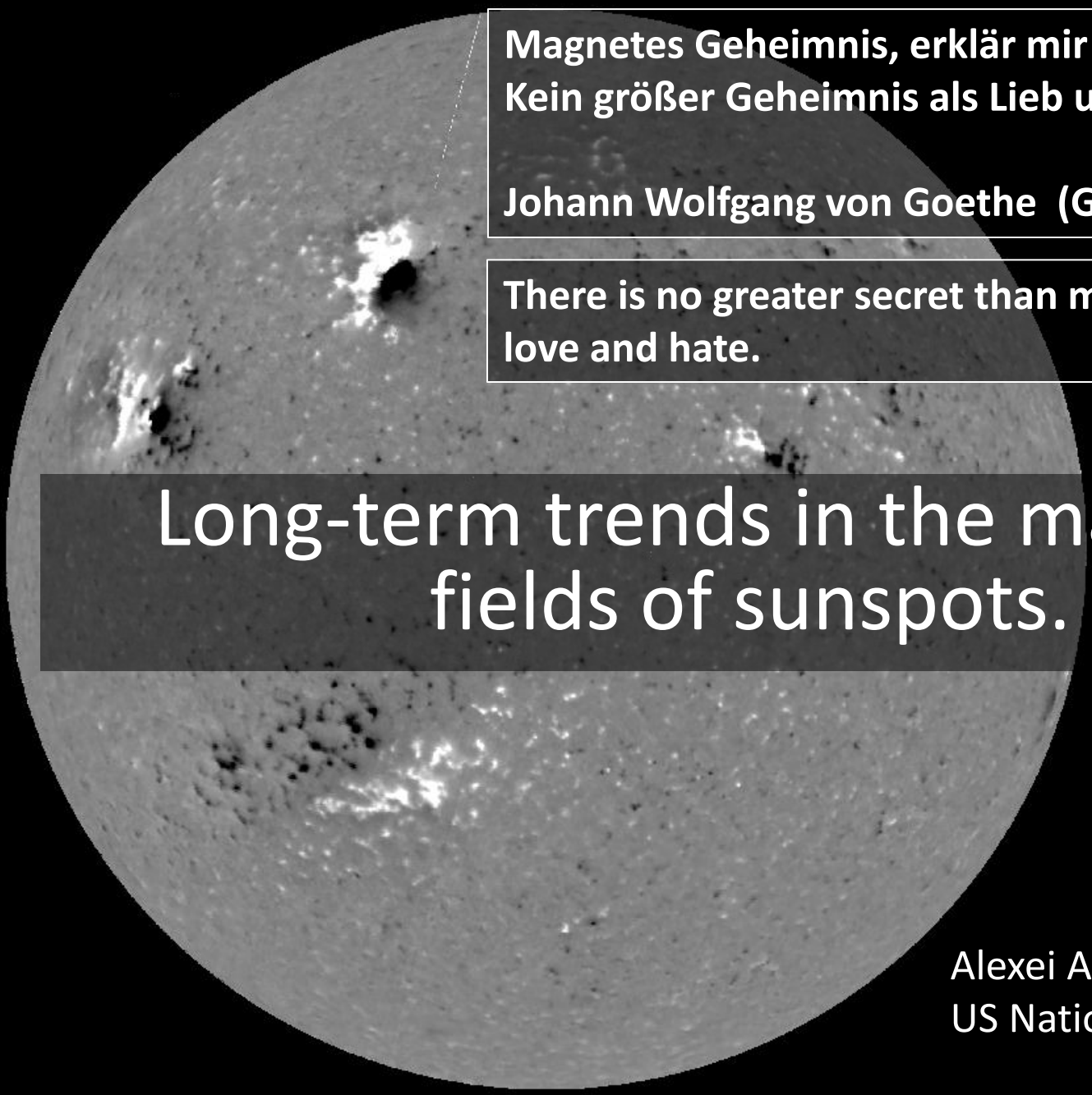


Magnetes Geheimnis, erklär mir das!
Kein größer Geheimnis als Lieb und Hass.

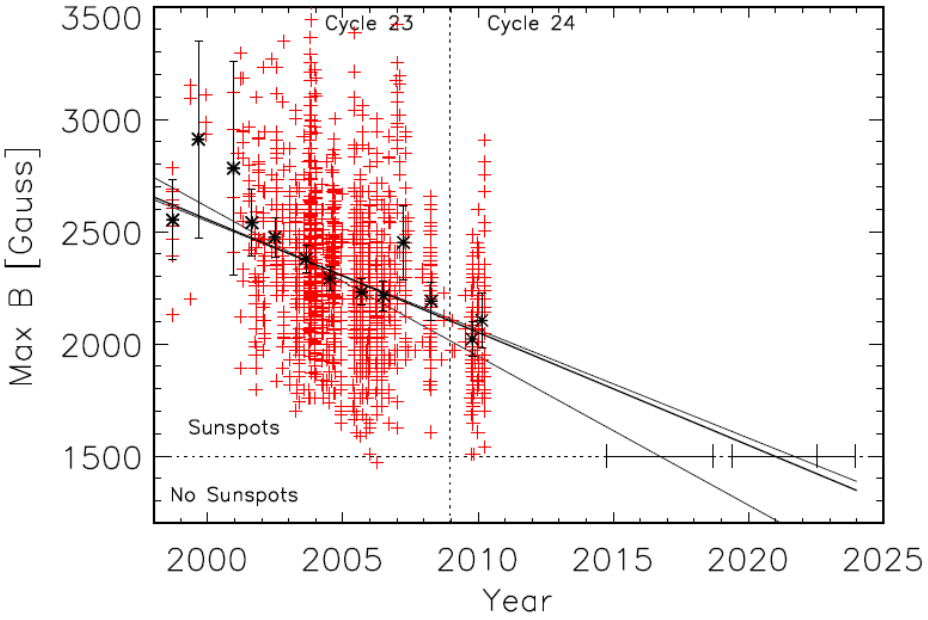
Johann Wolfgang von Goethe (Gott, Gemüt und Welt)

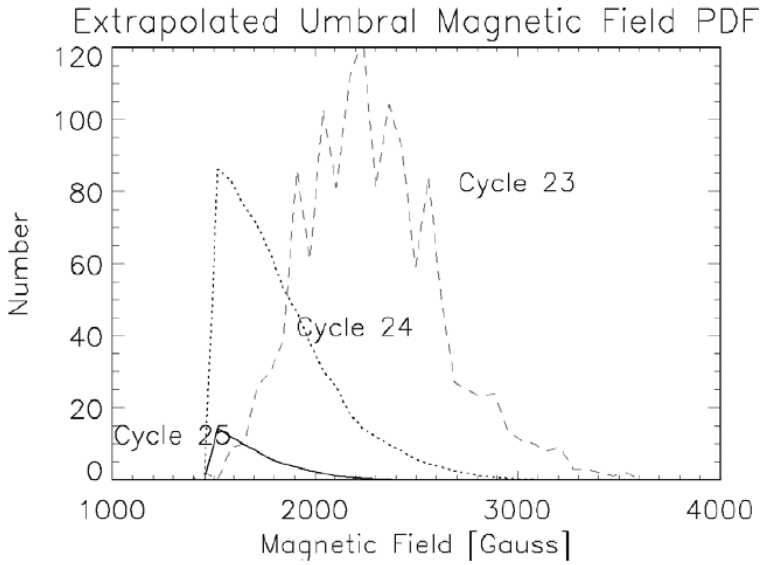
There is no greater secret than magnetism, except love and hate.

Long-term trends in the magnetic fields of sunspots.

Alexei A. Pevtsov
US National Solar Observatory

- Past attitude: "Sunspots are forever"

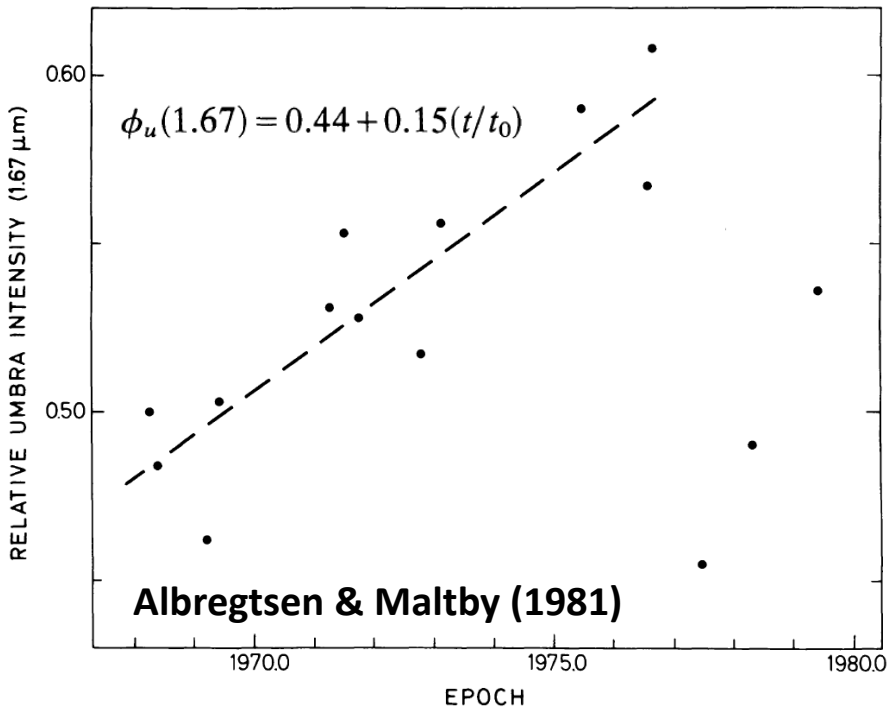




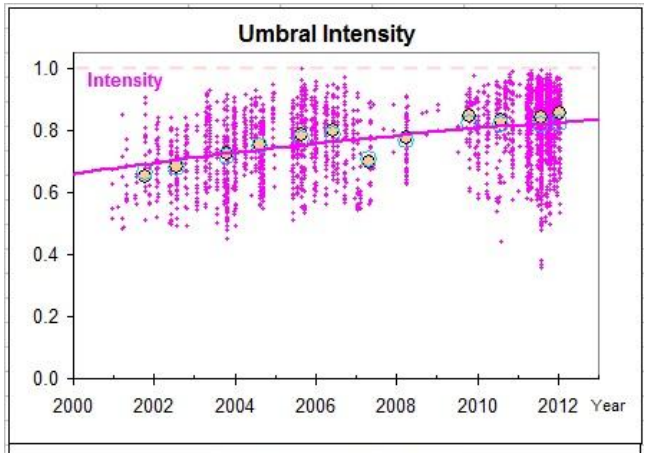
Penn and Livingston (2011)

Penn & Livingston (2006): decline in field strengths –52 G/year
Watson et al (2011) –70 G/year

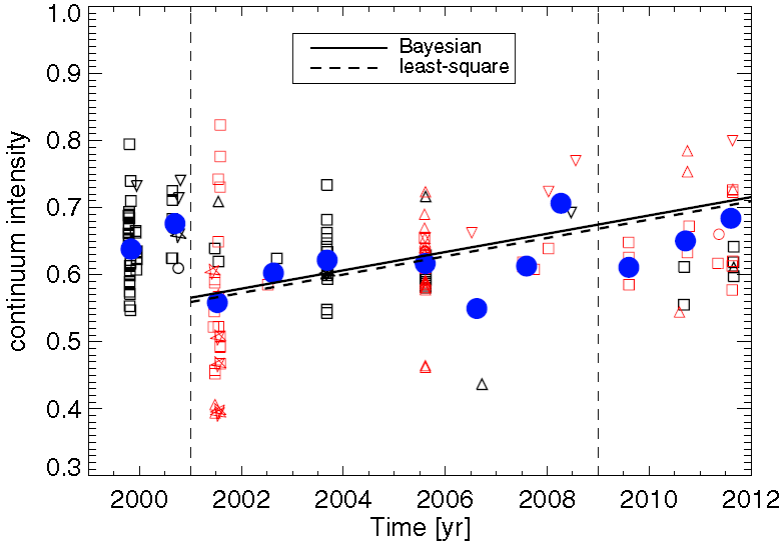
Cycle Variation in umbra intensity



Albregtsen & Maltby (1981)



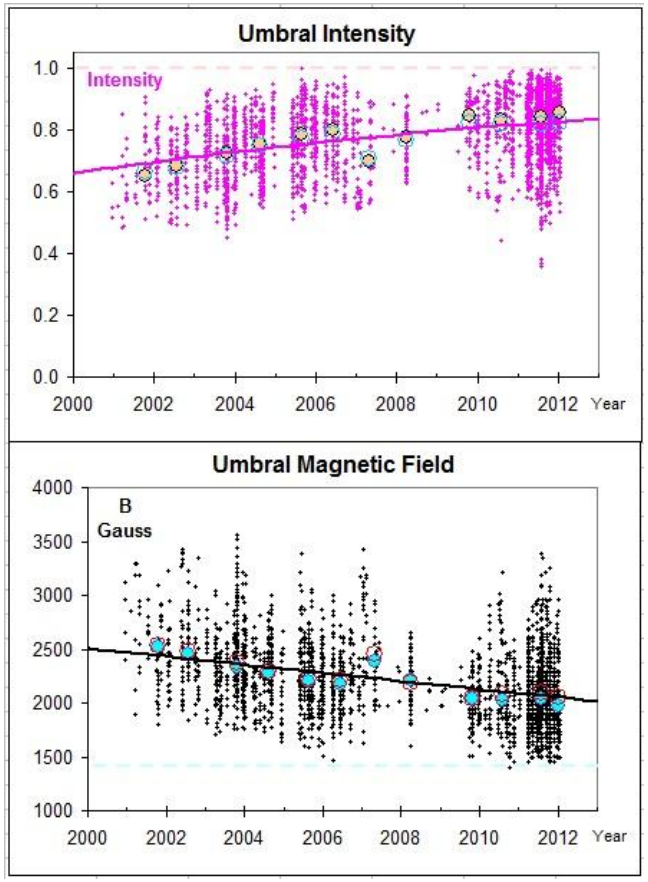
Livingston (2012, private communication)



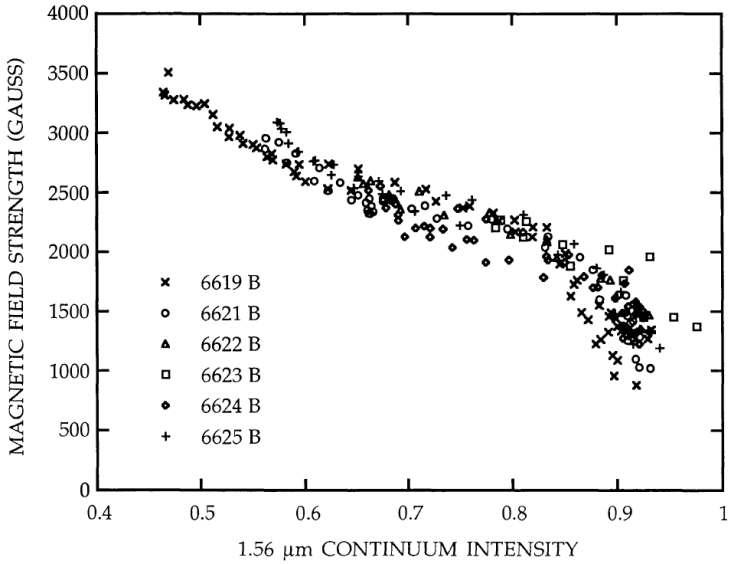
Rezaei, Beck, & W. Schmidt (2012)

- Penn & Livingston (2006): 1.9% /yr increase
- Mathew et al (2007) – (MDI, 160 spots 1998-2004) slight decrease in umbral intensity
- Schad & Penn (2010) – (>10000 umbra, KPVT/SPMG) no significant variation with cycle both intensity and field.

Brighter-weaker spots or Not?

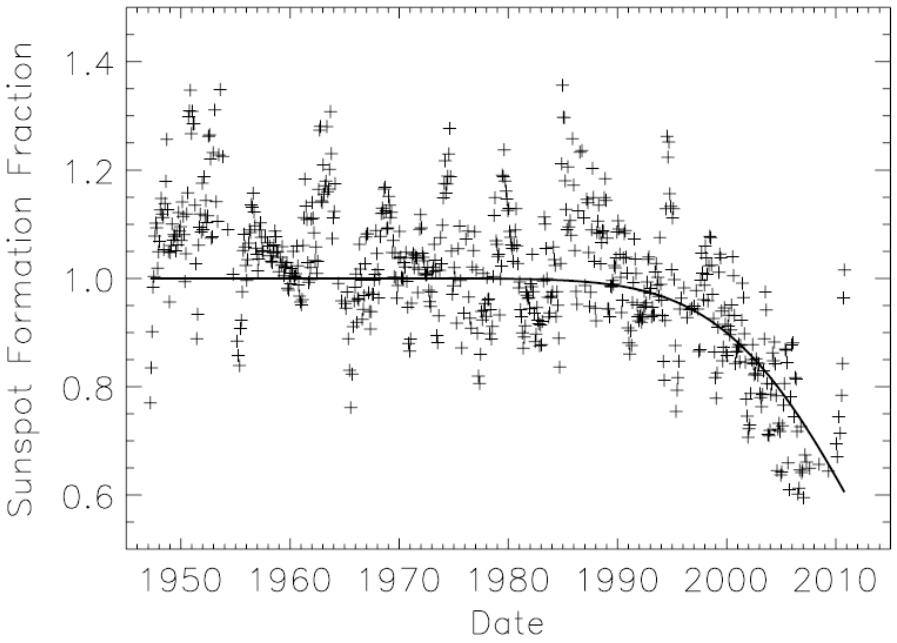


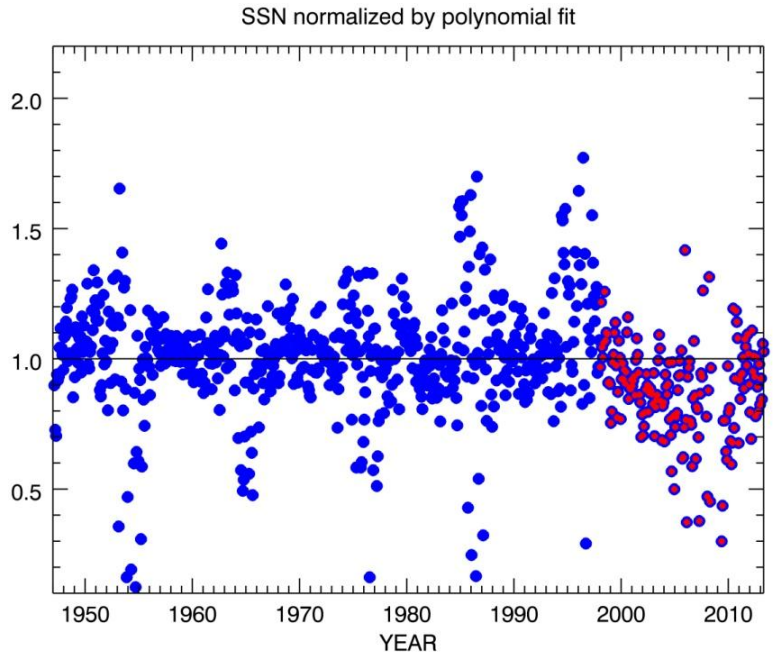
- Sunspots are getting brighter
- Their magnetic fields get weaker



Kopp & Rabin (1992)

Sunspot Field Strength and 10.7 cm Radio Flux





Livingston, Penn, Svalgaard (2012)

- PDF retains shape, mean shifting 46 G yr^{-1}
- Ratio of spots field strength to 10.7 cm flux anomaly consistent

Are Sunspots Weakening?

- Not as dark?
- Not as cold?
- Not as magnetic?

- If true, secular, cyclic or both?

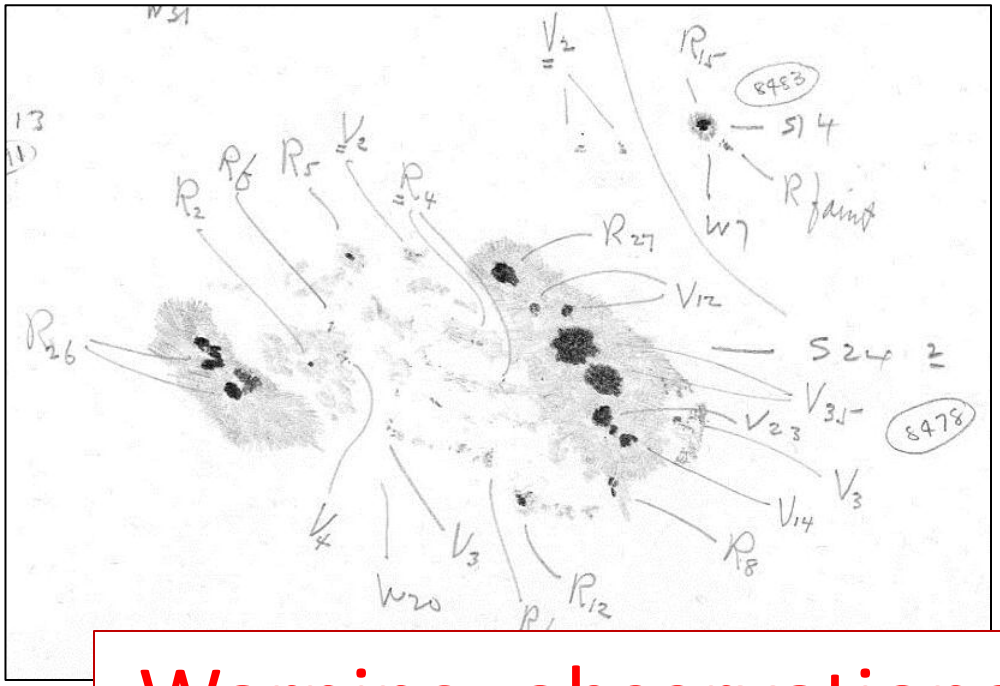
Relevant Data

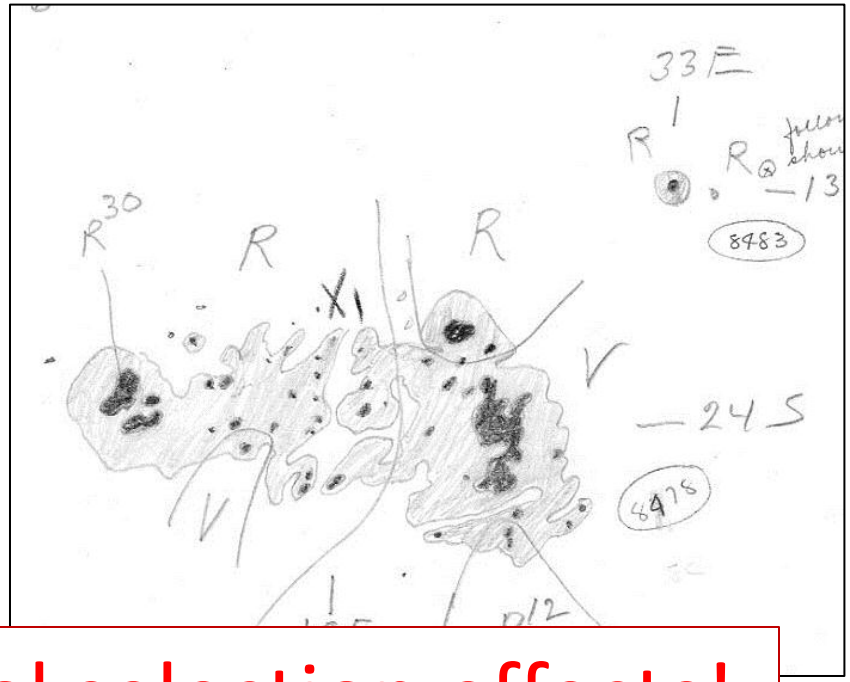
- "Old data" – 1957-2011; http://www.gao.spb.ru/database/mfbase/gindex.html

  (Pevtsov, A. A., Nagovitsyn, Y., Tlatov, A. and Rybak, A.: 2011, **Long-Term Trends in Sunspot Magnetic Fields,** ApJ, **742**, L36)
- "Newer data" – 1998-2012 http://solar.crao.crimea.ua/data/sunspots/

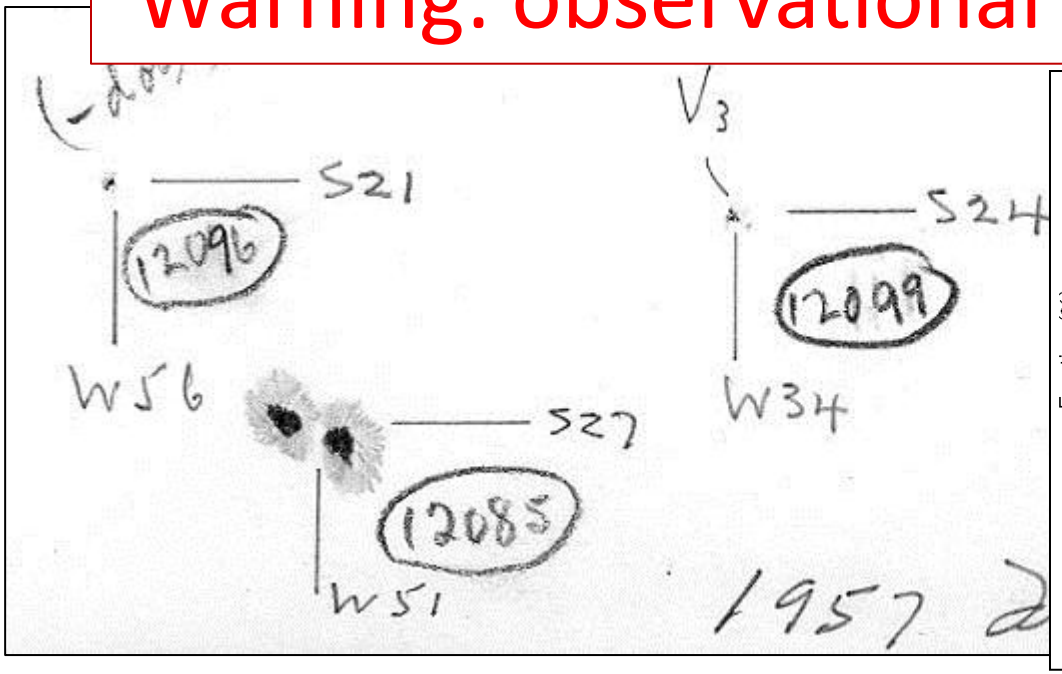
  (Nagovitsyn, Yu. A., Pevtsov, A.A., and Livingston, W.C.: 2012, **On a Possible Explanation of the Long-Term Decrease in Sunspot Field Strengths**, ApJ, **758**, L20)
- "Really old data" – 1920-1958; http://www.nso.edu/node/174

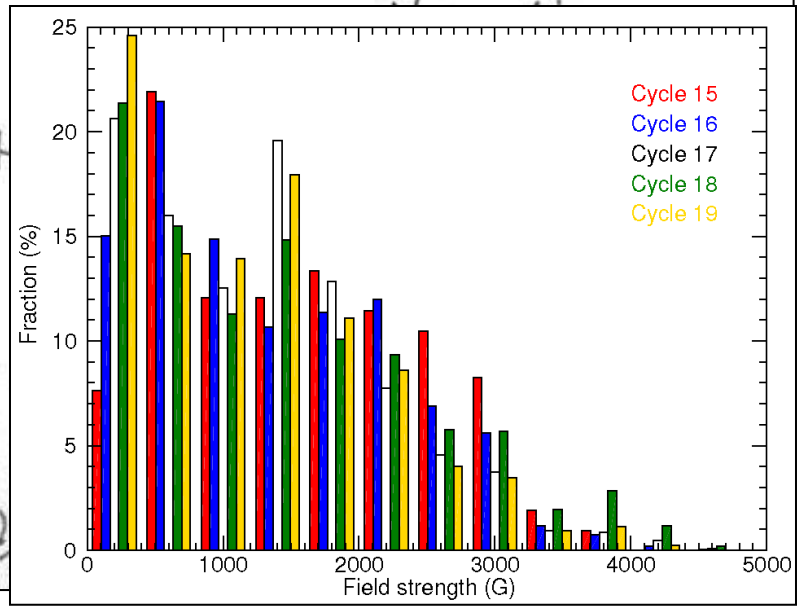
  (Pevtsov, A. A., Bertello, L., Tlatov, A. G., Kilcik, A., Nagovitsyn, Yu. A., Cliver, E. W.: 2013, **Cyclic and Long-term Variation of Sunspot Magnetic Fields**, Solar Physics, DOI: 10.1007/s11207-012-0220-5)



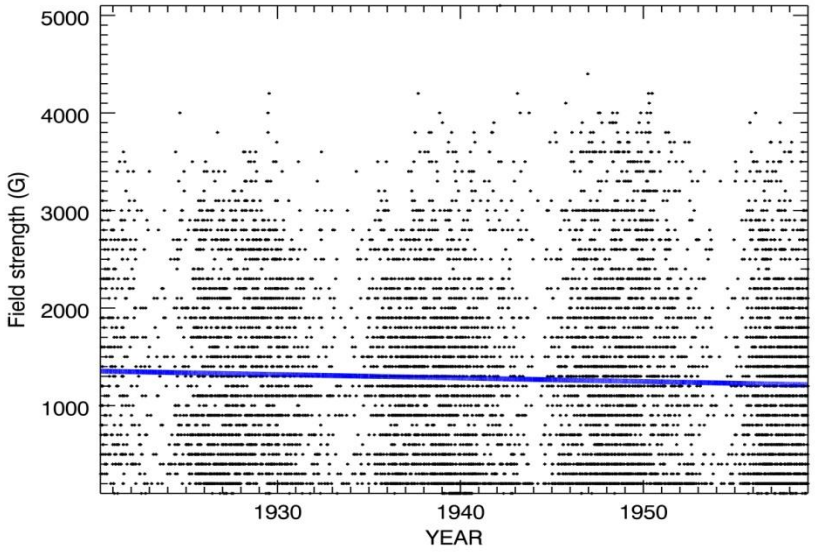


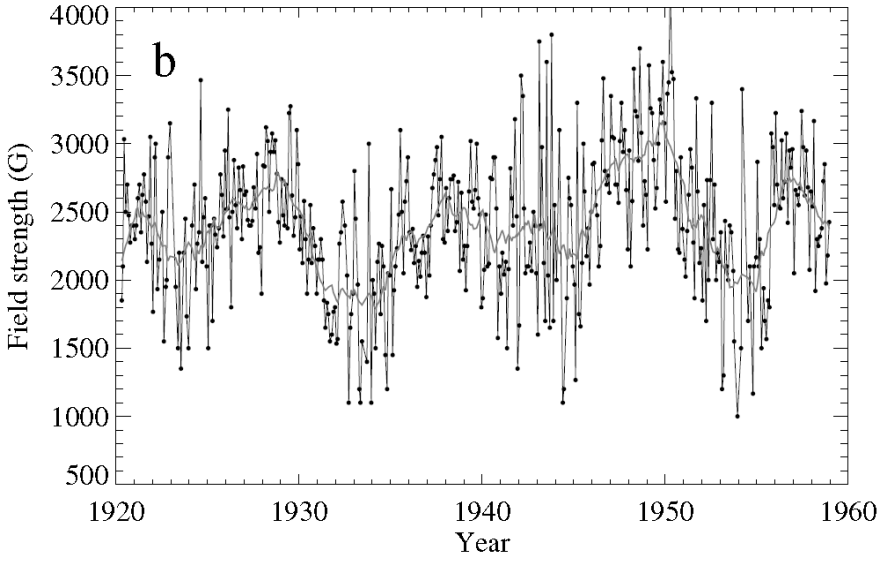
Warning: observational selection effects!





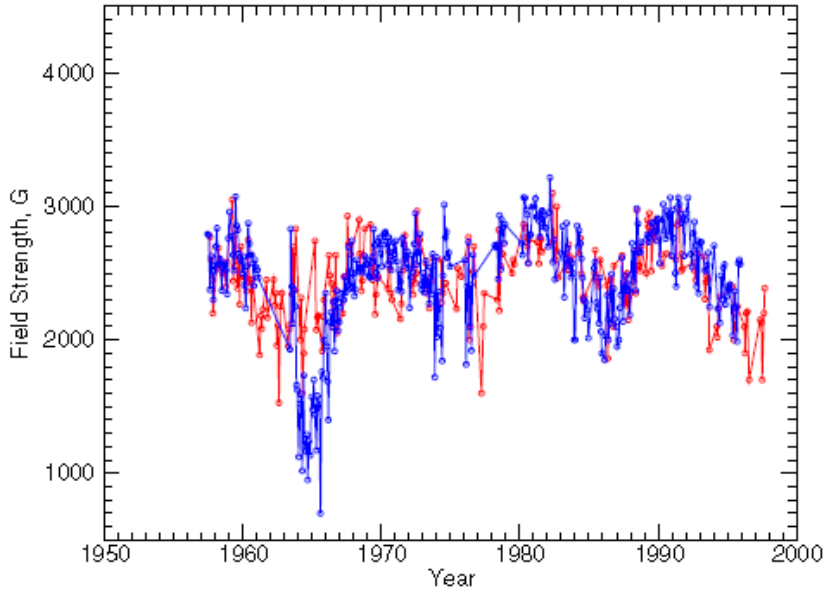
MWO Field Measurements

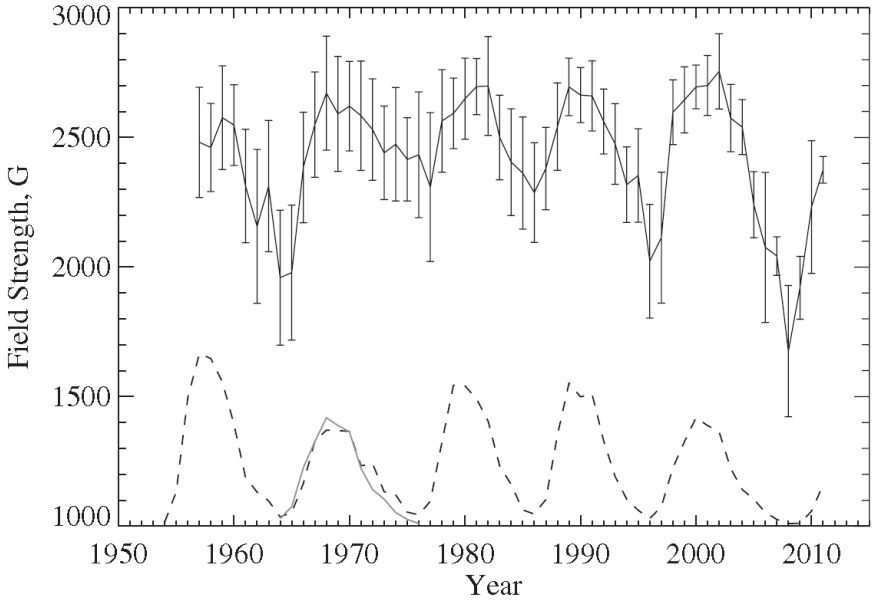




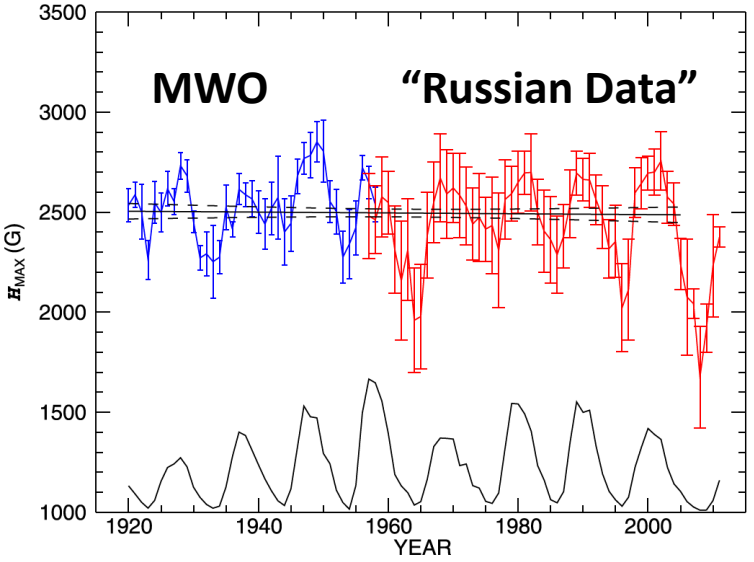
- Negligible decrease in sunspot field strength over 40 years of about 0.81 ± 7 G year^{-1}.
- Sunspots with the strongest field strength, show a clear solar cycle variations.

“Old” (Russian) Data Set

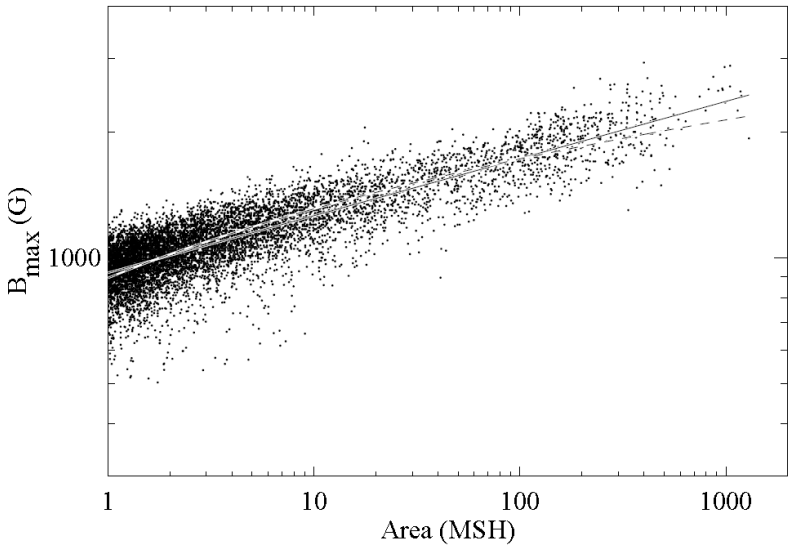




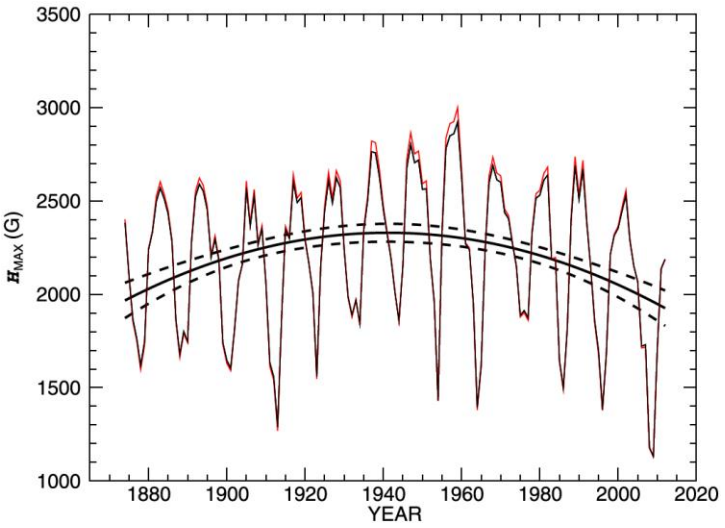
- Long-term trends may appear due to inclusion of smaller/weaker field features
- Strong fields show only variations with solar cycle, and no secular trend
- Penn & Livingston (2006): decline in field strengths –52 G/year
- Watson et al (2011) –70 G/year
- -83.5 G/yr (C19), -47.1 (C20), -97.9 (C21), -85.1 (C22), -118.7 G/yr (C23)



Area-Field Strength Relation



Tlatov & Pevtsov (2013)



Pevtsov et al (2013)

- Solar cycle variations with amplitude about 1000 G
- Magnetic field proxy shows variations with solar cycle
- Much weaker secular trend (300 G increase-decrease) with a broad maximum in 1950th – Gleissberg Cycle?

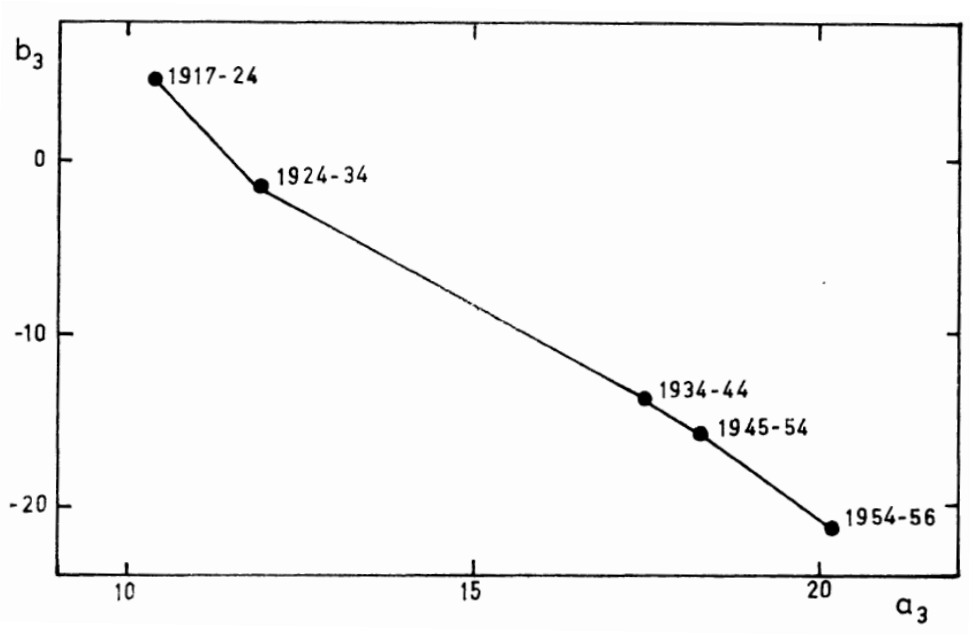
Changes in Area-Field Relation

Table 2 Correlation (ρ) and fitted coefficients for the $H = A + B \times \ln(S)$ dependency between magnetic field strength (H) and the deprojected area (S) of an active region. Student's t-values and maximum sunspot number (SSN) for the $(n+1)$-th cycle are also shown.

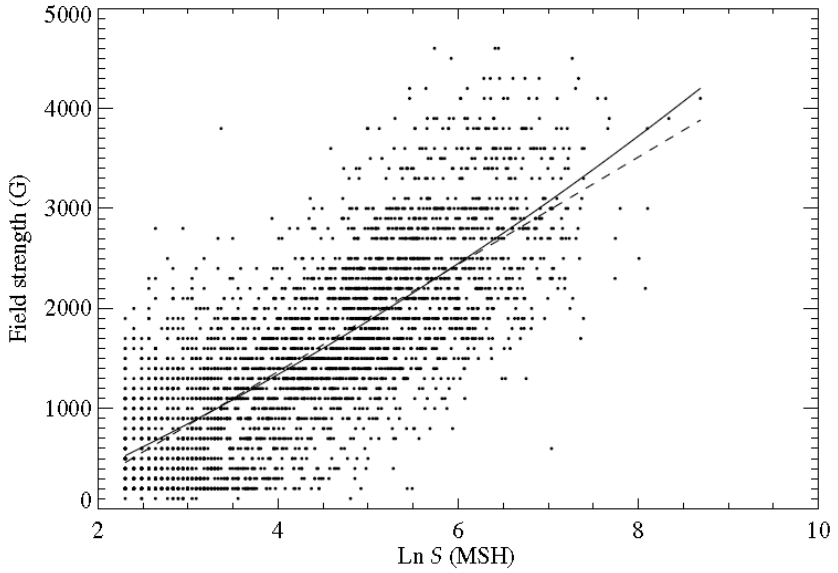
Cycle No.	A	B	ρ	t-value	99 %-level	SSN_{n+1}
Cycle 15	-274.1 ± 177.6	507.3 ± 40.2	0.775	12.633	2.623	78.1
Cycle 16	-475.1 ± 63.4	514.9 ± 13.9	0.811	36.947	2.583	119.2
Cycle 17	-771.0 ± 59.9	523.2 ± 13.2	0.781	39.595	2.581	151.8
Cycle 18	-1106.9 ± 78.9	609.2 ± 16.9	0.739	35.966	2.580	201.3
Cycle 19	-800.4 ± 69.5	495.4 ± 14.9	0.784	33.252	2.583	110.6
All cycles	-774.2 ± 35.6	536.0 ± 7.7	0.756	69.170	2.577	
Cycles 16–18	-806.3 ± 41.0	551.7 ± 8.9	0.761	61.670	2.578	

Pevtsov et al (2013)

Changes in Area-Field Relation

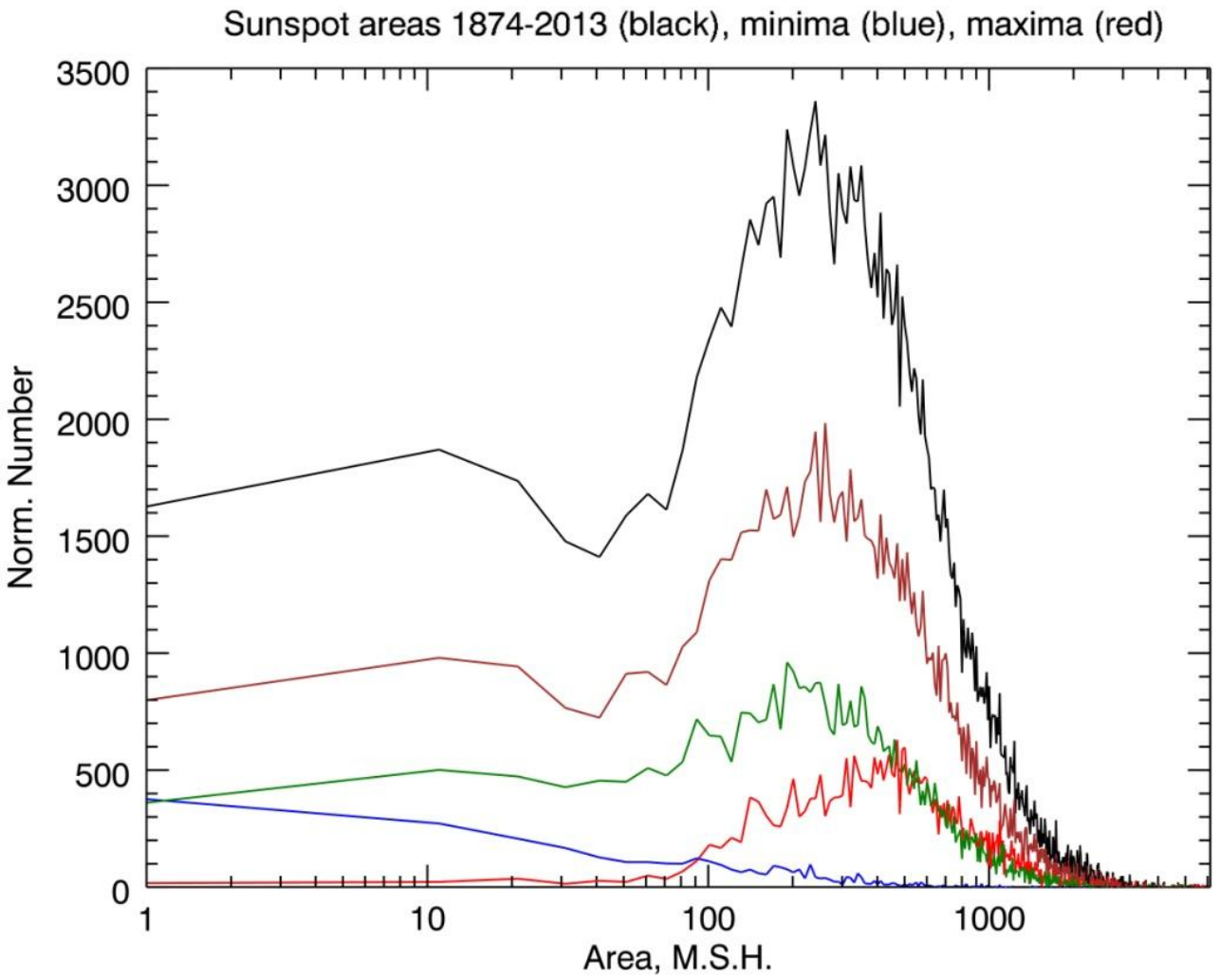


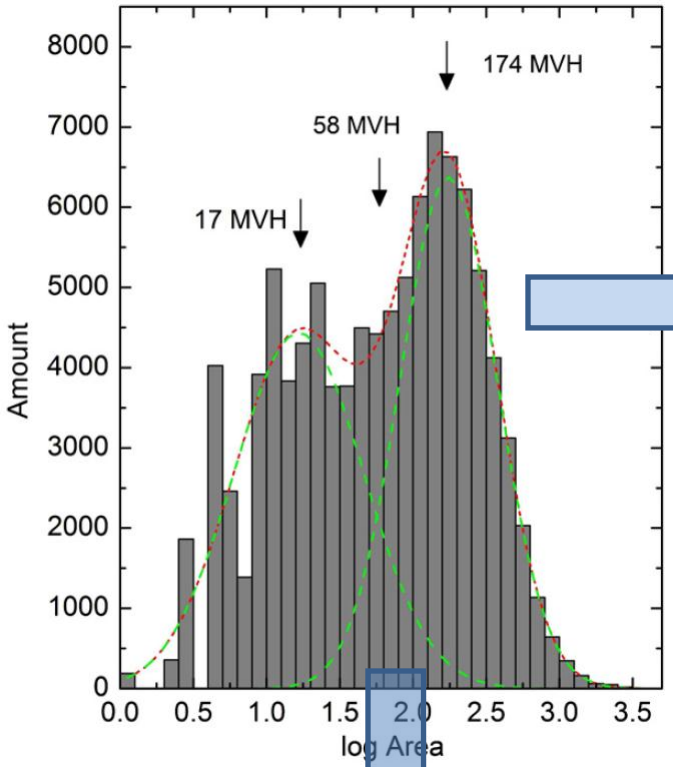
Ringnes & Jensen (1960): $H=a_3 \log A_p + b_3$



Pevtsov et al (2013)

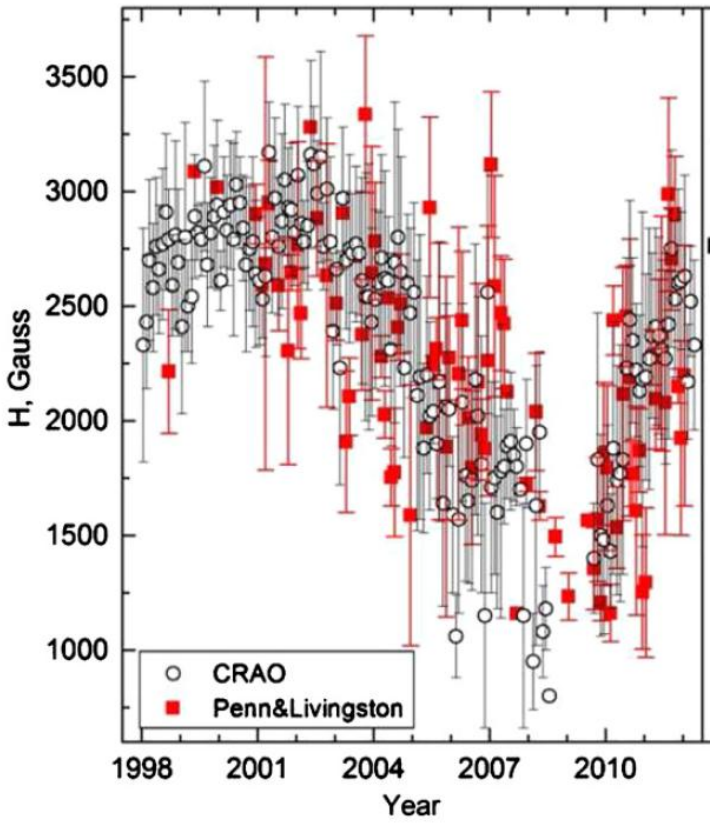
- Can be explained by changes in fraction of small or large sunspots


Sunspot areas 1874-2013 (black), minima (blue), maxima (red)
Norm. Number
3500
3000
2500
2000
1500
1000
500
0
1
10
100
1000
Area, M.S.H.

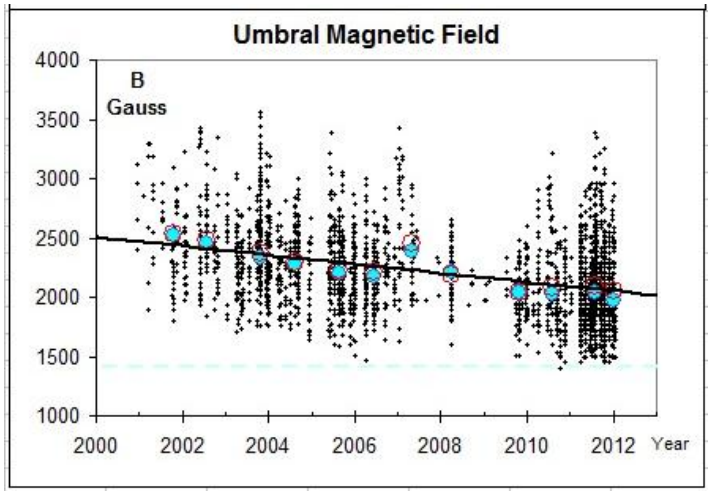


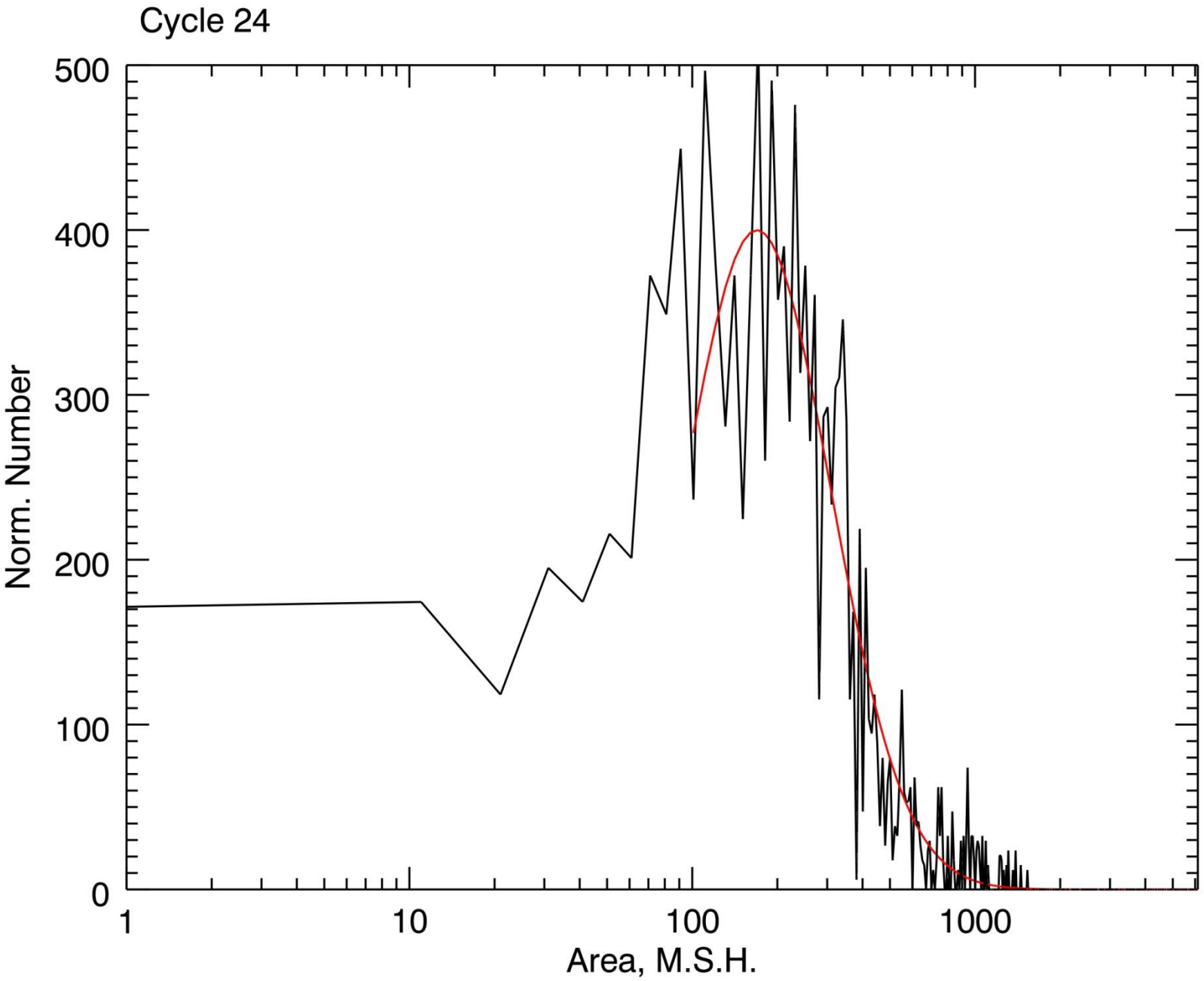
Nagovitsyn et al (2012)

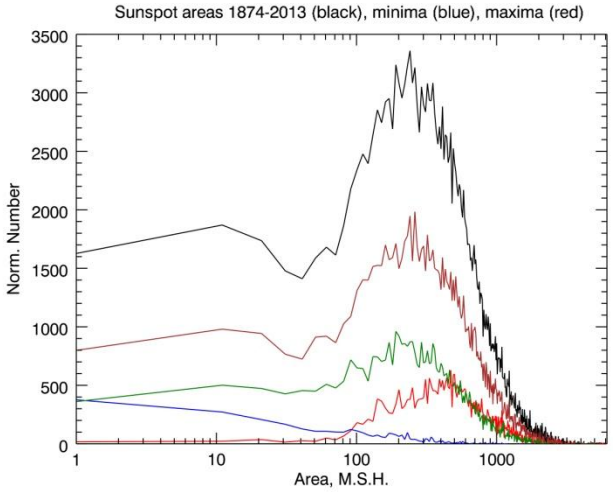
Large sunspots contribution

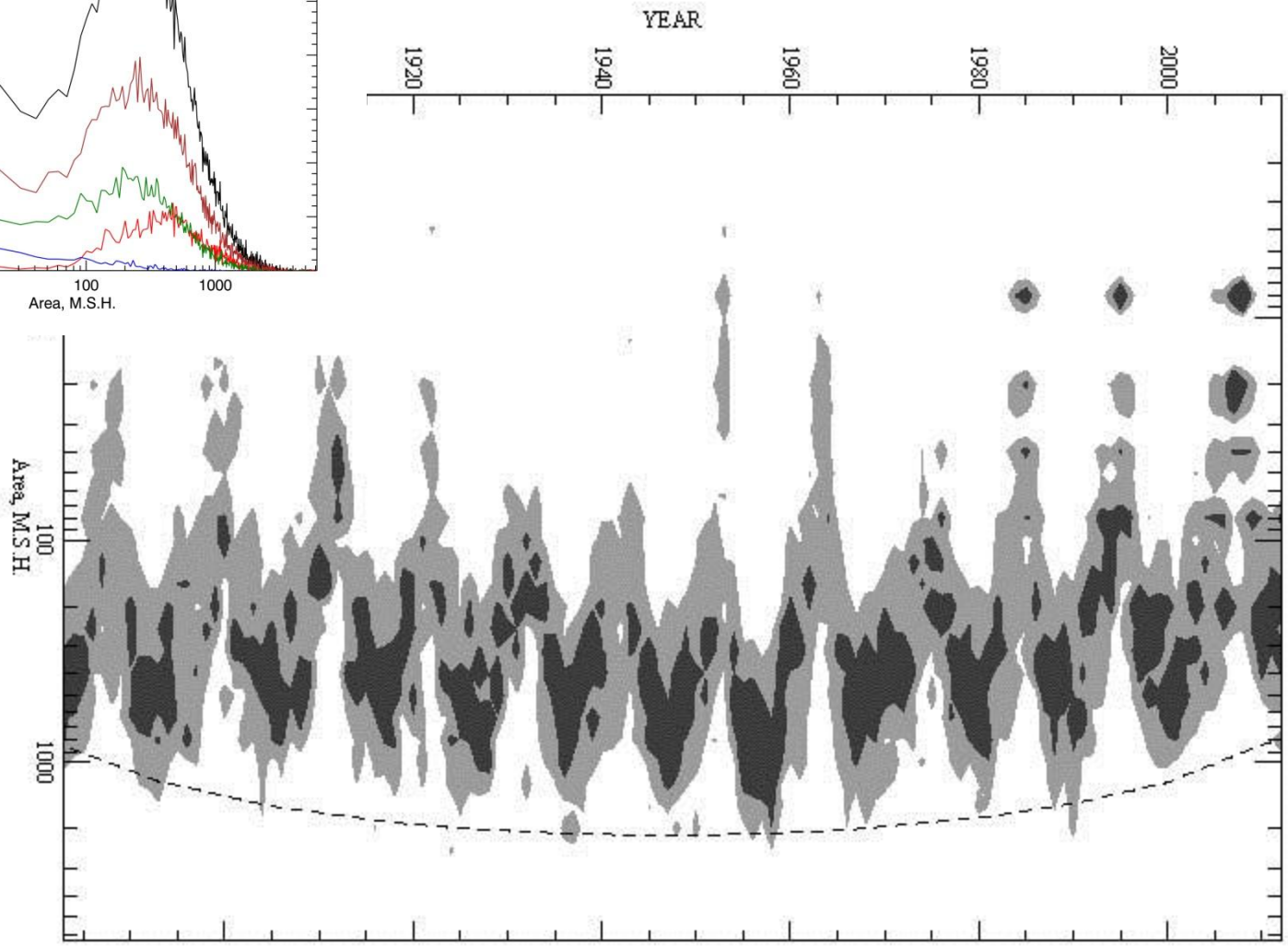


Mean of two contributions

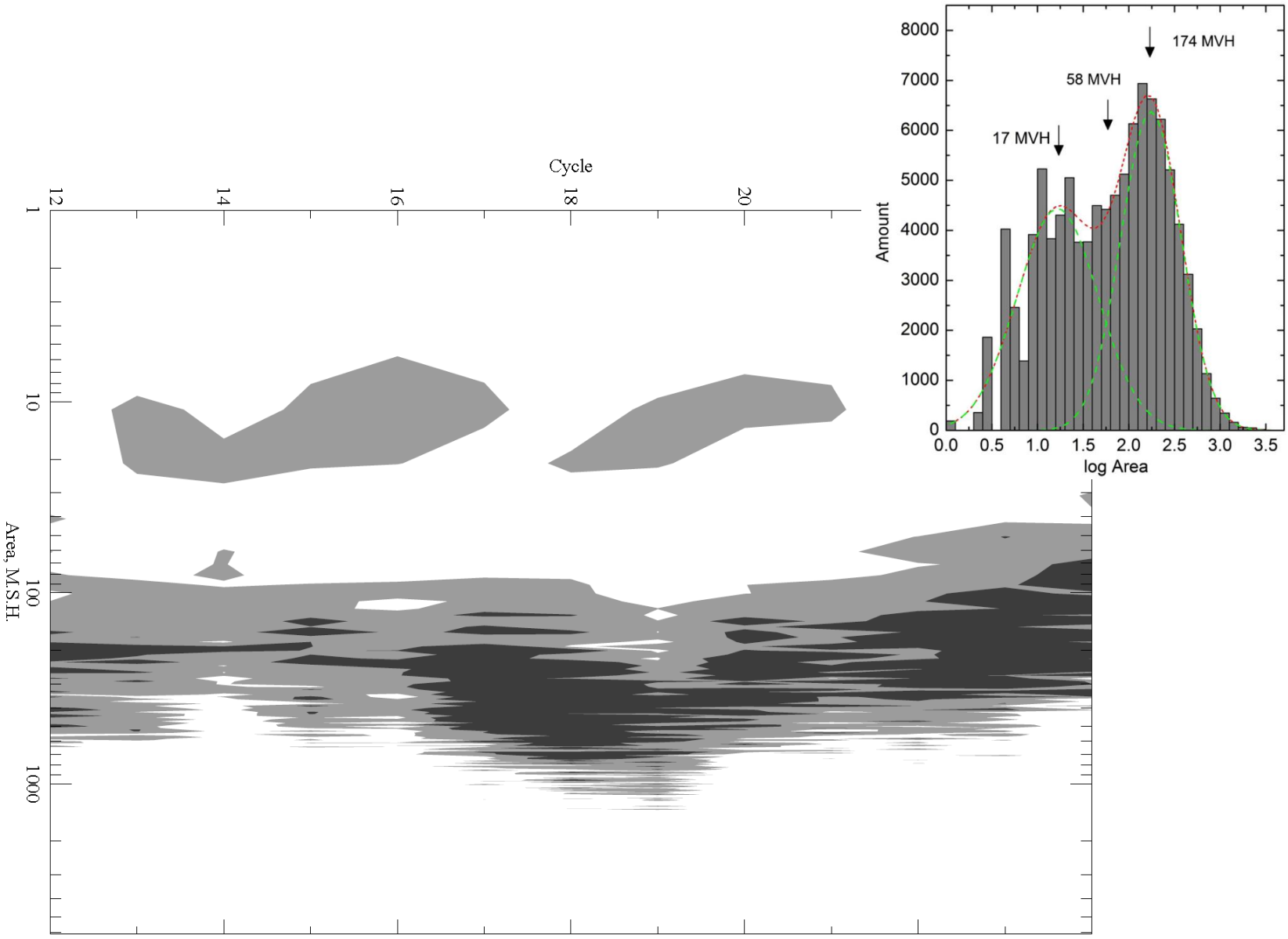


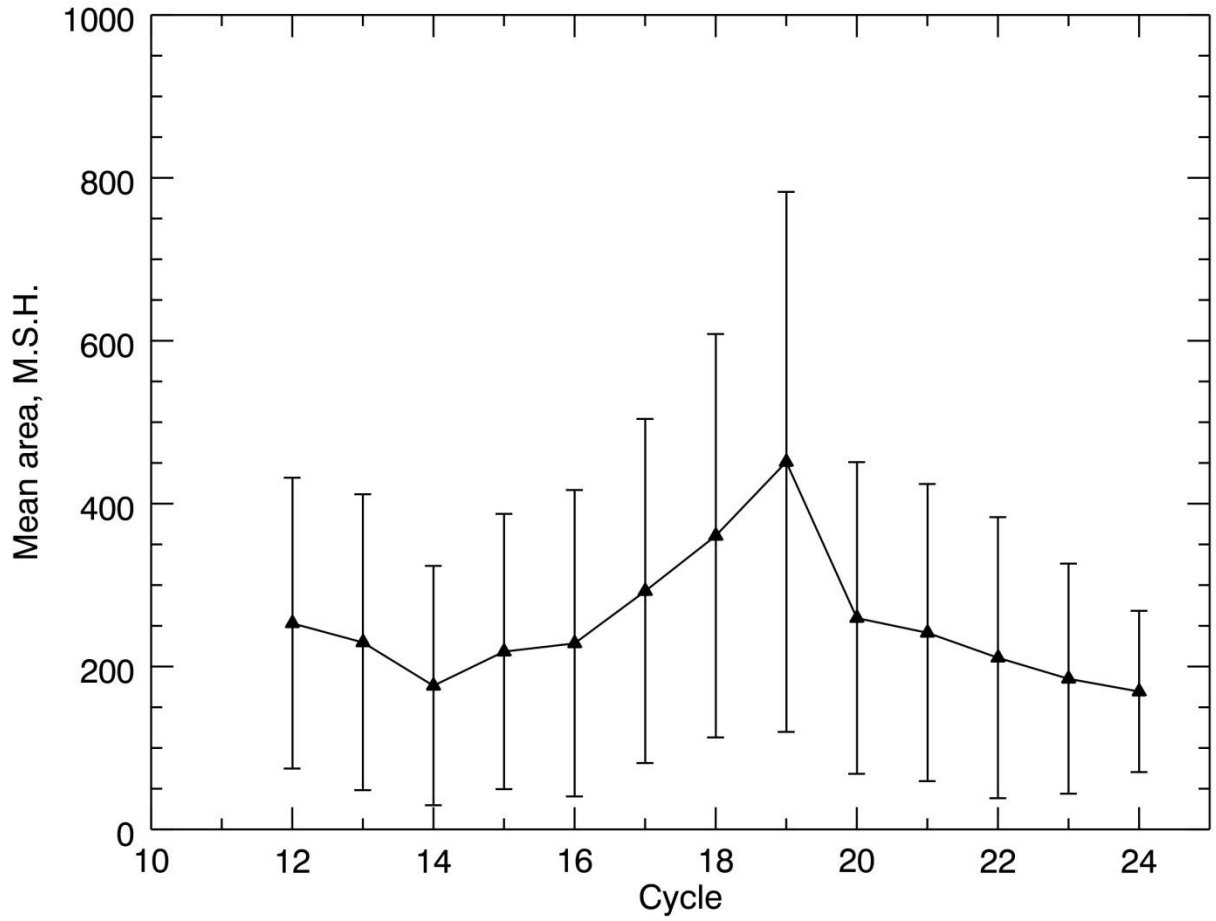

Cycle 24
500
400
300
200
100
0
Norm. Number
1
10
100
1000
Area, M.S.H.



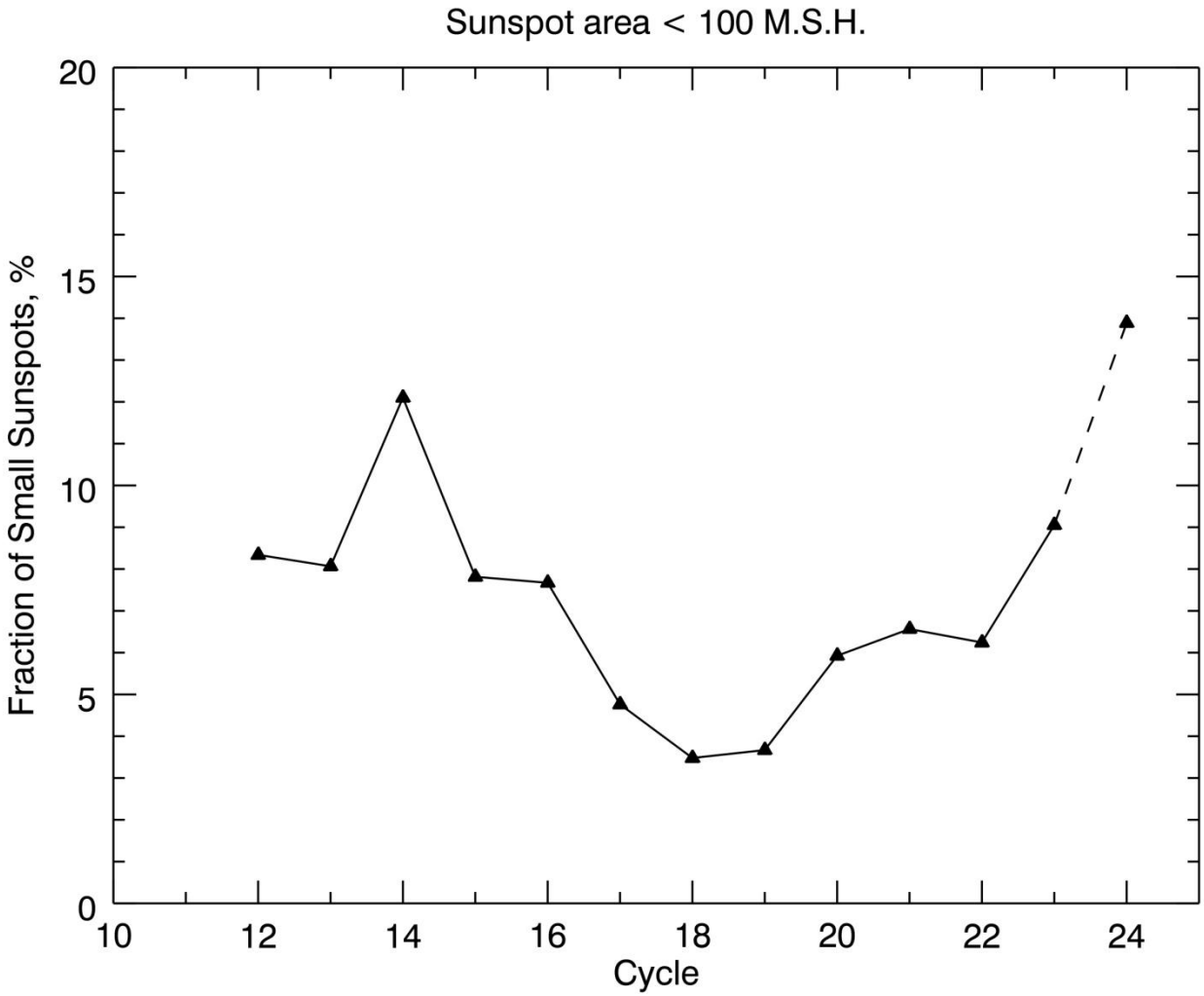


- A weak secular trend with a broad maximum in 1950th – Gleissberg Cycle?


Cycle
12
14
16
18
20
Area, M.S.H.
1
10
100
1000
Amount
8000
7000
6000
5000
4000
3000
2000
1000
0
0.0
0.5
1.0
1.5
2.0
2.5
3.0
3.5
log Area
174 MVH
58 MVH
17 MVH

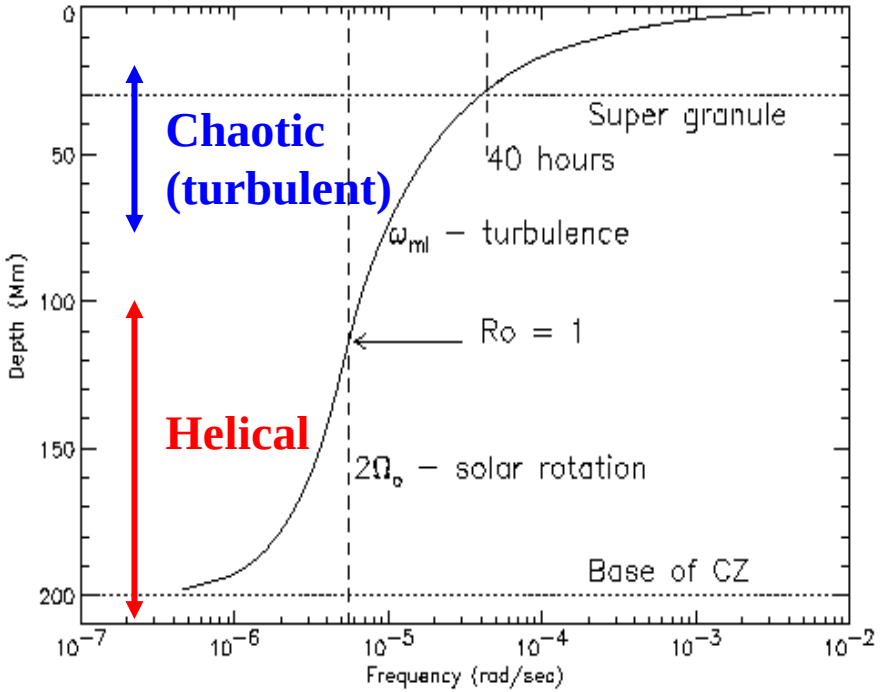


• Mean of distribution of sunspot areas and width of distribution vary with height of cycle

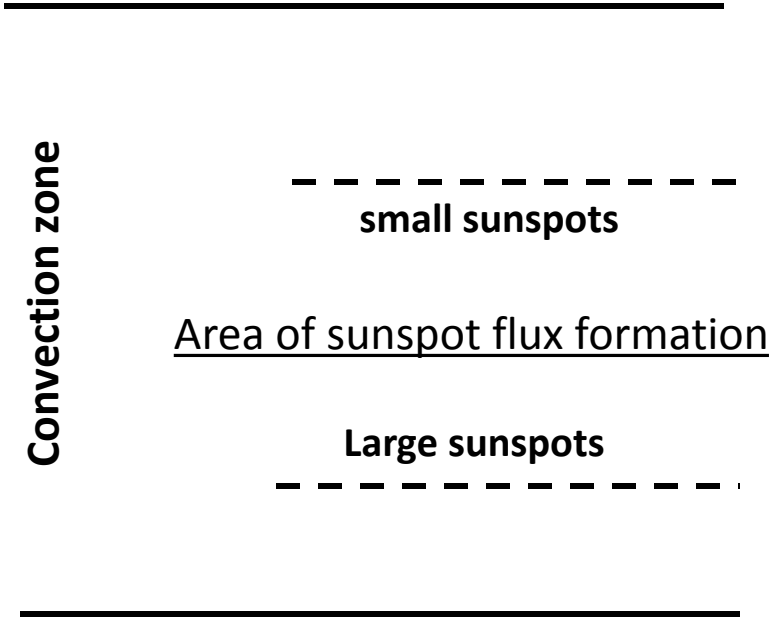


- Fraction of small area sunspots shows long-term trends

What does it all mean?



Pevtsov & Longcope (2007)



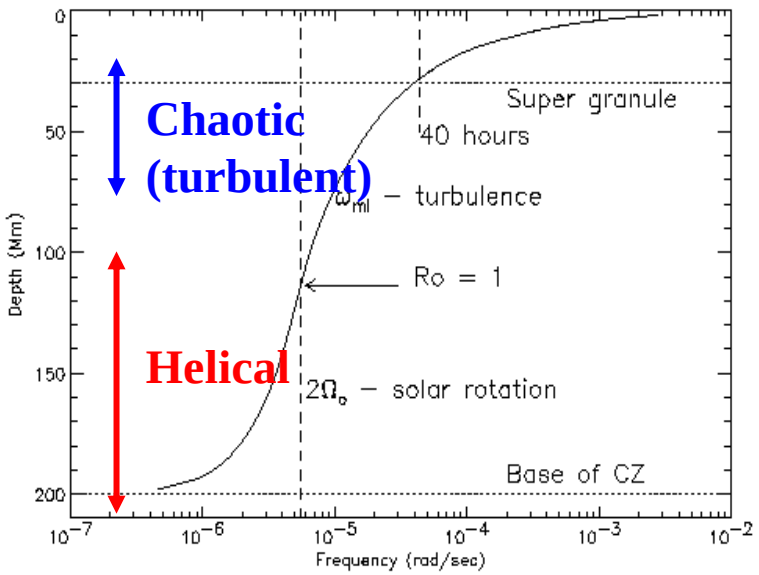
$$Ro = \frac{v}{2L\Omega} = Co^{-1}; v, L - \text{typical velocity and length},$$

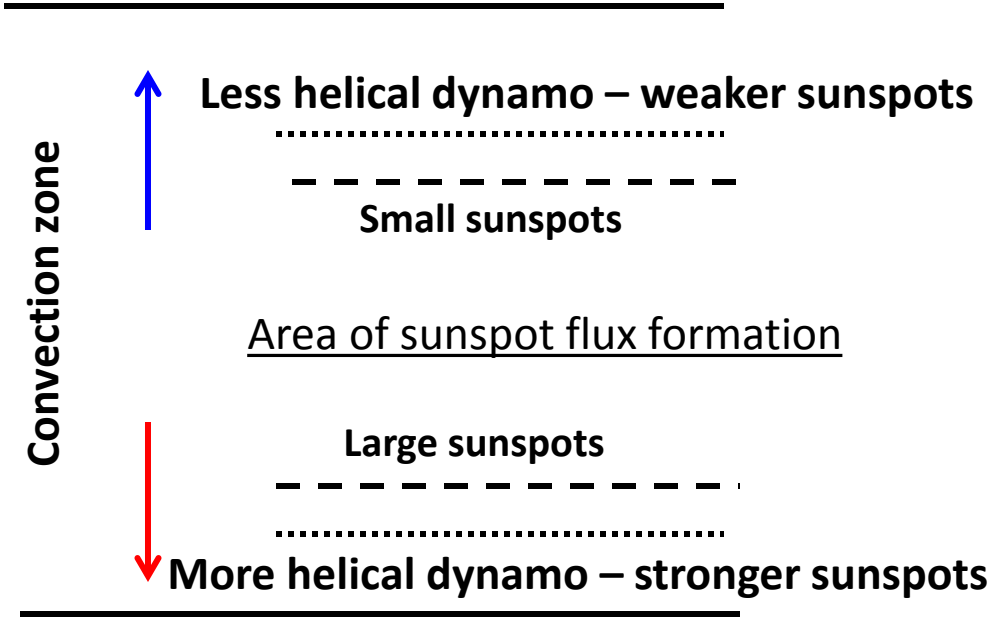
Ω is angular velocity.

$Ro >> 1$ – Coriolis force has no effect.

$Ro << 1$ – Coriolis force is a dominant effect.

What does it all mean?

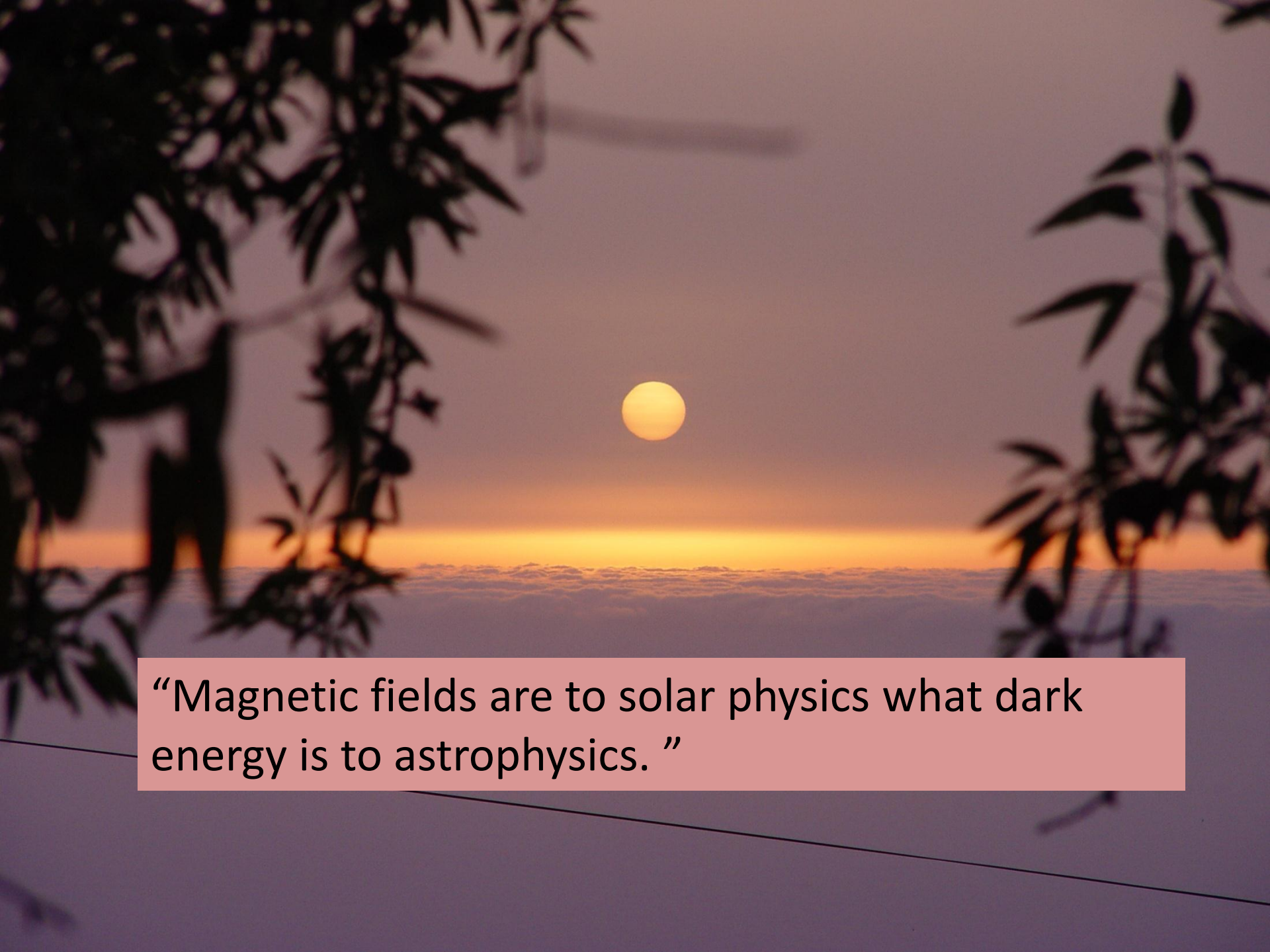




• Changes in depth of sunspot flux formation may increase/decrease fraction of sunspots with stronger/weaker field strength.

Concluding Remarks

- Sunspot field strength vary with solar cycle (solar min/max – weaker/stronger sunspots)
- Long-term (100-years) trends are present, but show much smaller amplitude than cycle variations.
- Both cycle and long-term variations may be related to changes in sunspot size distribution
- Could it be explained by changes in location of sunspot flux formation zone in CZ?


“Magnetic fields are to solar physics what dark energy is to astrophysics. ”