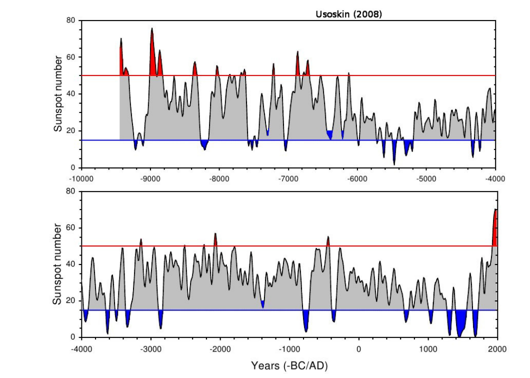
Long-term trends in properties of sunspots

Reza Rezaei[1]

in collaboration with
C. Beck[2], M. Collados[1], J. M. Borrero[3] A. Lagg[4], W. Schmidt[3]

1- Instituto de Astrofísica de Canarias (IAC), Tenerife, Spain
2- National Solar Observatory, Boulder, Colorado, USA
3- Kiepenheuer-Institut für Sonnenphysik, Freiburg, Germany
4- Max Planck Institute for Solar System Research, Göttingen, Germany

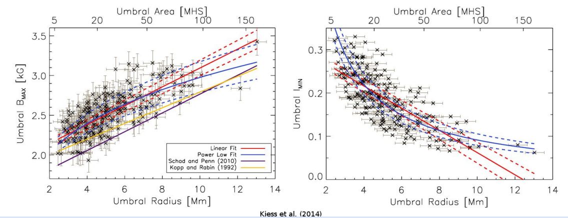
Long term variability of the solar cycle

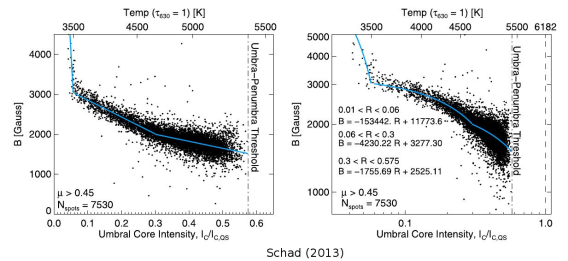


- ★ tracers: radioisotopes like ^{14}C or ^{10}Be
- ★ A stochastic component is essential to the solar cycle.

Usoskin (2008); McCracken et al. (2013)

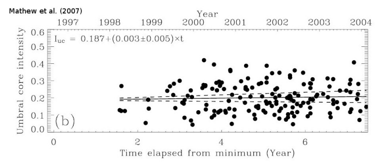
Sunspot properties: $B - I - R$

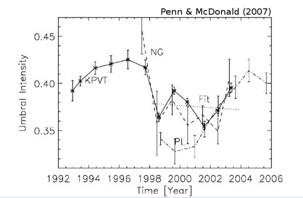


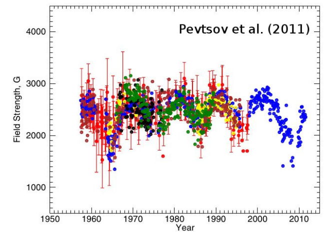


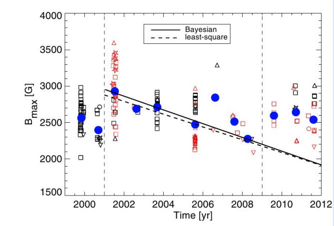
Kiess, Rezaei, & Schmidt (2014); Schad (2013)

Sunspot properties during a solar cycle



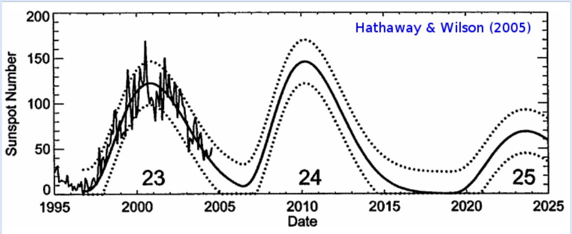




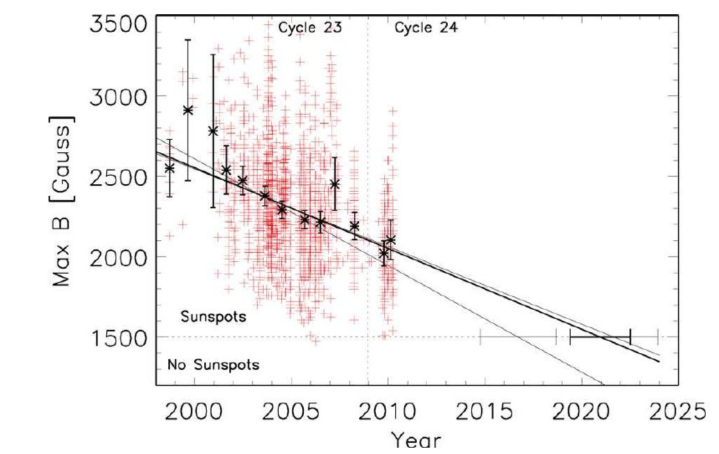


- ★ Umbrae brighten/darken in the decaying/rising phase of a solar cycle. (Albregtsen & Maltby (1978); Penn & Livingston (2006); Norton & Gilman (2006); Penn & MacDonald (2007); Mathew et al. (2007); Rezaei et al. (2011).
- ★ Field strength modulates with the phase of the solar cycle Rezaei et al. (2011; 2015); Nagovitsyn et al. (2011); Pevtsov et al. (2011); Watson et al. (2011).

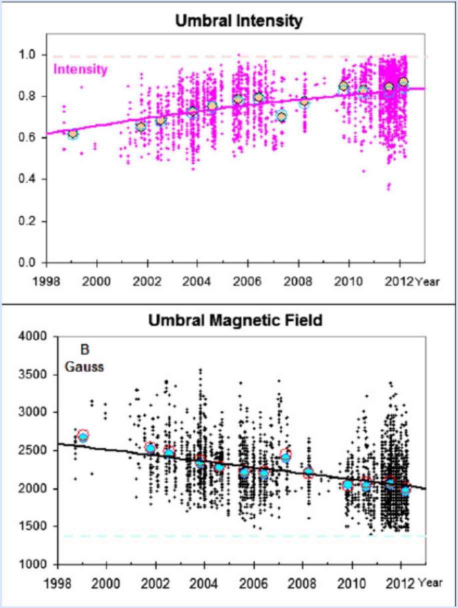
The extended minimum of cycle 23 triggered questions ...



- ★ Sunspots in cycle 23 had smaller field strength compared to cycle 22 (Livingston 2002).
- ★ Penn & Livingston (2011) as well as Livingston et al. (2012) predict a monotonic decrease of sunspot field strength, with no sunspots in cycle 25.
- ★ Several authors confirmed a cyclic variation. There is a controversy about a long-term trend.

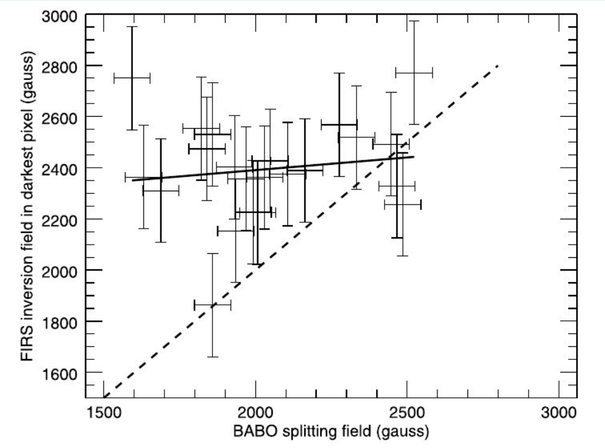


Penn & Livingston (2011)



Livingston et al. (2012)

Cross-calibration of McMath and DST data



Watson, Beck, Penn, Tritschler, Martinez-Pillet, and Livingston (2015)

Cyclic variation vs. long-term trend

- ★ Penn & Livingston (2011) find a long-term trend in solar activity with a weak cycle 24 and no sunspots in cycle 25.
- ★ Pevtsov et al. (2011) recover increase and decrease of the B_{max} during five solar cycles. No long-term trend.
- ★ Rezaei et al. (2011) find a rate of -93$\pm$14 G yr^{-1} for the sunspot field strength in decaying phase of cyclic 23.
- ★ Livingston et al. (2012) find a long-term rate of -46$\pm$6 G yr^{-1}.
- ★ Nagovitsn et al. (2012) find cyclic trend in Penn & Livingston data.
- ★ Schad (2013) find that mean magnetic field strength does not show a significant long term trend.
- ★ Watson et al. (2014) find a decrease of 375 G in sunspot magnetic fields over the period 1996-2013 corresponding to -22 G yr^{-1}.
- ★ Rezaei et al. (2015) find a long-term rate of -7$\pm$4 G yr^{-1} for the sunspot field strength in addition to the cyclic variation.

Observations: 463 full Stokes sunspot maps in infrared

- Tenerife Infrared Polarimeter (TIP) at VTT
  - ★ 1999–2006 TIP I (Martinez Pillet et al. 1999)
  - ★ 2006–2014 TIP II (Collados et al. 2007)

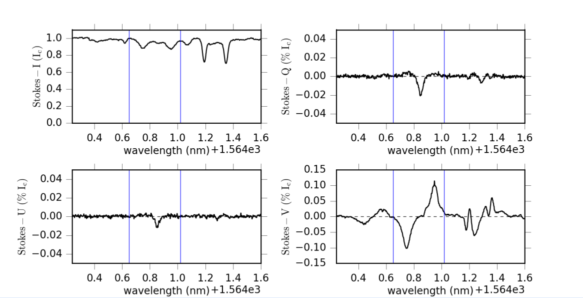
- Facility Infrared Spectropolarimeter (FIRS) at DST
  - ★ 2013–2015 FIRS (PI: H. Lin; Univ. Hawaii)

- Spectro-Polarimeter for Infrared and Optical Regions (SPINOR) at DST
  - ★ 2014–2015 SPINOR (Socas-Navarro et al. 2006)

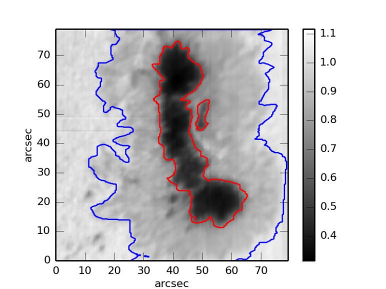
- GREGOR Infrared Polarimeter (GRIS) at GREGOR
  - ★ 2014–2015 GRIS (Collados et al. 2012)

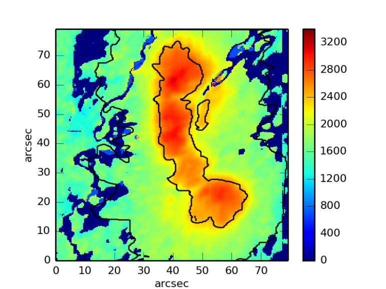
Spectral lines

- Full Stokes spectra
  - ★ Fe I 1078.3 nm, $g_{eff} = 1.5$
  - ★ Si I 1082.7 nm, $g_{eff} = 1.5$
  - ★ Fe I 1089.6 nm, $g_{eff} = 1.5$
  - ★ Fe I 1564.8 nm, $g_{eff} = 3.0$



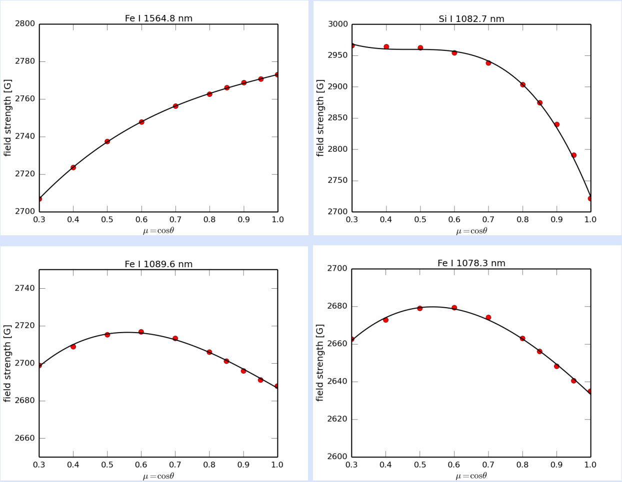
Sample map





- some 570 datasets were evaluated.
- Duplicated observations were discarded.
- No pore.
- No sunspot at $\mu < 0.3$.
- Uncertainties: fringes, molecular lines, stray light, gradients, ...

CLV of the field strength in our spectral lines

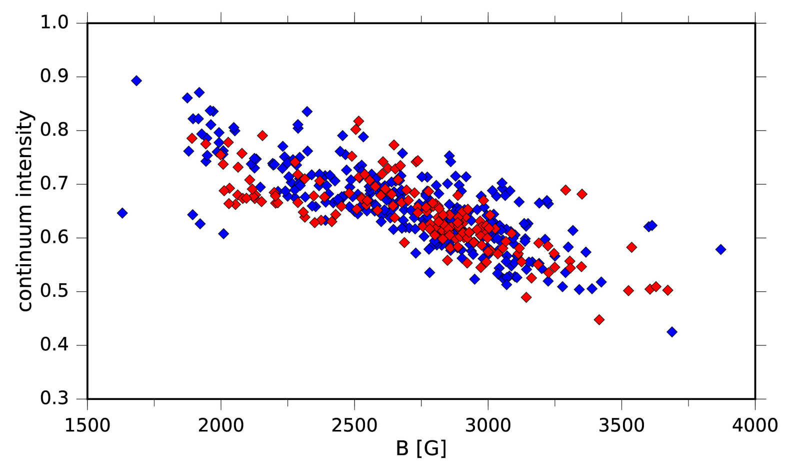


(Maltby et al. 1986; Collados et al. 1994; Ruiz Cobo & del Toro Iniesta 1992)

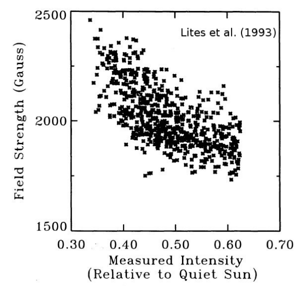
Scaling the magnetic field strength and continuum intensity

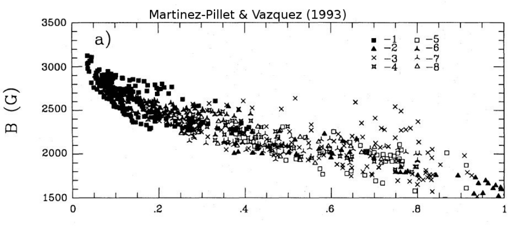
- M-model of of Maltby et al. (1986) with magnetic field stratification from cool-model of Collados et al. (1994).
- spectral lines were synthesized in each case using SIR.
- Stokes-*V* profiles were analyzed like observed data. Hence each line returns a value for the field strength.
- Fixed offset was added to Fe I 1078.3 and Fe I 1089.6 nm.
- Magnitude of correction is comparable to ΔB due to limited accuracy in fitting maximum/minimums (spectral dispersion).
- Empirical relation between continuum intensities at 1.08 and 1.56 μm ranges: $\boxed{\mathrm{I}_{1.56} = (I_{1.08} + 0.246)/1.0918}$
- umbral limb-darkening : Albergtson, Joras, & Maltby (1984).

Continuum intensity vs. B_{max}



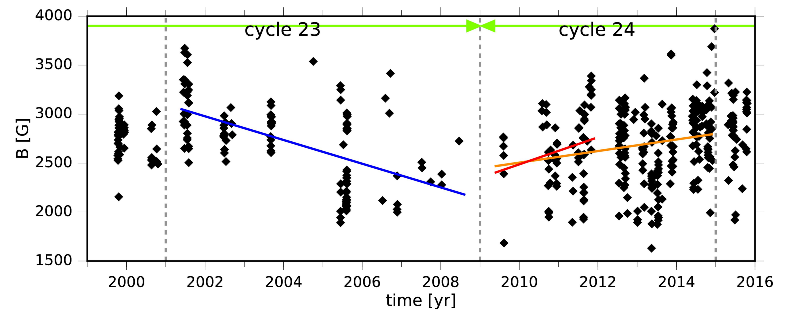
intrinsic scatter





(Lites et al. 1993; Martinez-Pillet & Vazquez 1993)

Temporal evolution of field strength

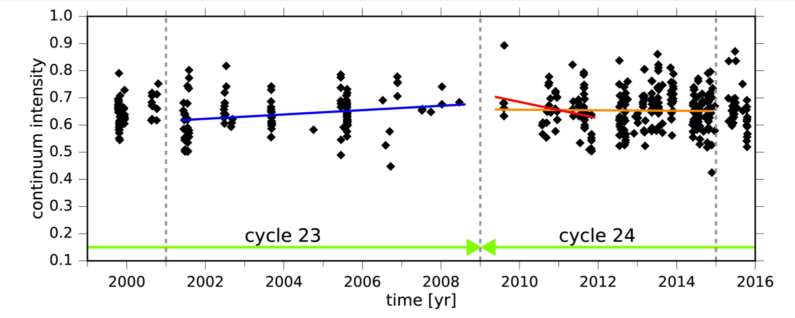


2001-2009: slope B_{max} = -121 ($\pm$ 7) G yr^{-1}

2009-2012: slope B_{max} = +138 ($\pm$ 30) G yr^{-1}

2009-2015: slope B_{max} = +59 ($\pm$ 7) G yr^{-1}

Temporal evolution of continuum intensity

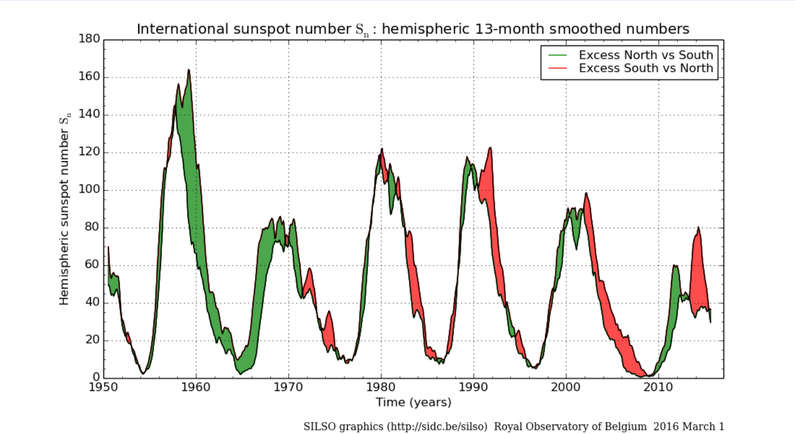


2000-2009: slope I_c = +0.8 (± 0.1) % I_c yr^{-1}

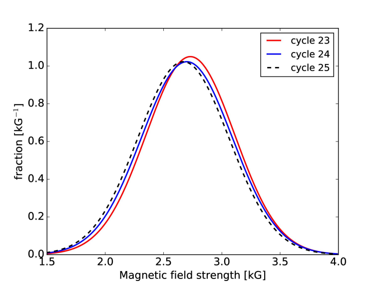
2009-2012: slope I_c = -3. (± 0.2) % I_c yr^{-1}

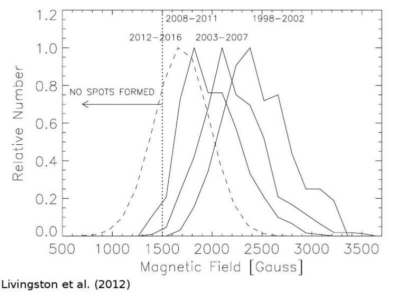
2009-2015: slope I_c = 0.1 (± .1) % I_c yr^{-1}

North-South Asymmetry



long-term variation

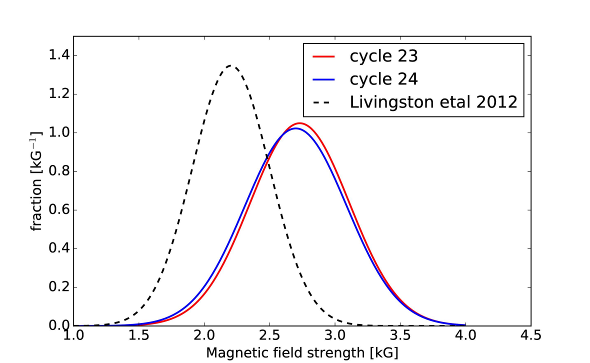




This work

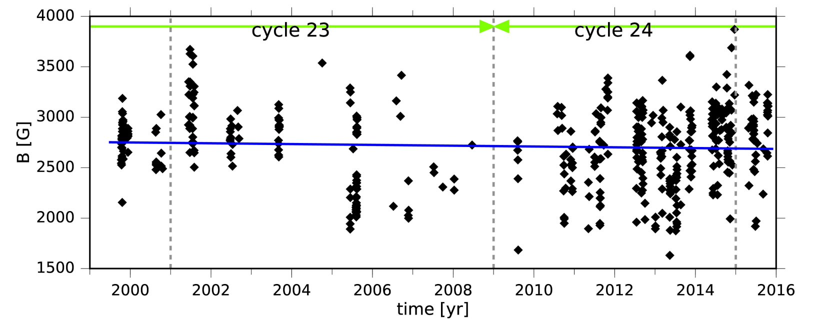
Livingston et al. (2012)

long-term variation



shift between the two cycles in our data = 30 $\pm$ 10 G

long-term slope



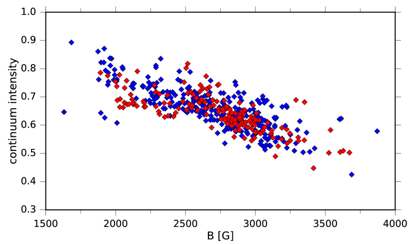
slope = -4 ± 1 G/yr $\equiv$ 44 G / cycle

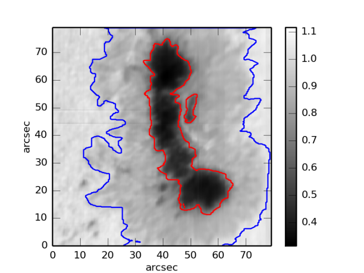
Comparison of long-term trend to previous studies

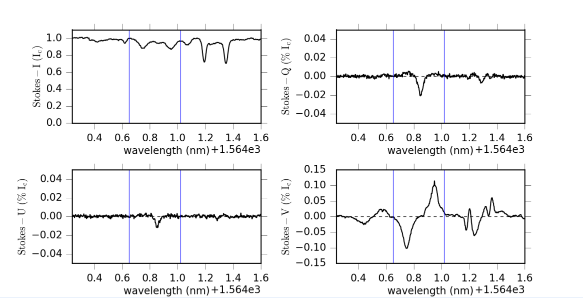
Pevtsov et al. 2011	no trend	Pulkovo, Crimean
Livingston et al. 2012	-46 ± 6 G yr^{-1}	McMath
Schad 2013	no trend	Hinode
Watson et al. 2014	-22 G yr^{-1}	McMath, MDI, HMI
Rezaei et al. 2015	-7 ± 4 G yr^{-1}	VTT, DST
This work	-4 ± 1 G/yr	VTT, DST, GREGOR

issues: polarized light, temporal coverage, 2D spatial information, AO, spectral sampling, ...

Comparison to other data sets







Summary

Sample 185 $\Rightarrow$ 374 $\Rightarrow$ 463

Cycle 23 We find a rate of $\boxed{-121 \pm 7\,\mathrm{G\,yr^{-1}}}$ for B_{max} and $\boxed{+0.8 \pm 0.1\%\,I_c\,\mathrm{yr^{-1}}}$ for the continuum intensity.

Cycle 24 We find a rate of $\boxed{+138 \pm 30\,\mathrm{G\,yr^{-1}}}$ for B_{max} and $\boxed{-3.0 \pm 0.2\%\,I_c\,\mathrm{yr^{-1}}}$ for the continuum intensity.

Long-trem trend Slope of a long-term decrease of the field strength is about $(-4) \pm 1$ G/yr.

Conclusion

1. Sunspot properties in cycle 24 are similar to cycle 23.
2. The amplitude of the cyclic variation is an order of magnitude larger than any long-term trend.
3. We find no argument in favor of a significant decrease of sunspot field strengths in cycle 25.