Solar activity in the following decades based on the results of the ISSI/VarSITI Forum on future evolution of solar activity, 01.03-03.03.2015 ISSI, Bern, Switzerland

Obridko V., Georgieva K.

June 6-10, 2016, Bulgaria

Project SEE
(Solar Evolution and Extrema)

Cochairmen D.Nandi, P.Martens, V. Obridko

ir Goals and Objectives:

1) Reproduce magnetic activity as observed in the Sunspot and cosmogenic records in dynamo simulations,

2) Amalgamate the best current models and observations for solar spectral and wind output over the Earth's history, and

3) Determine the size and expected frequency of extreme solar events such as flares and coronal mass ejections (CMEs).

Main Questions:

1) **Are we at the verge of a new grand minimum? If not, what is the expectation for cycle 25?**

2) Does our current best understanding of the evolution of solar irradiance and mass loss resolve the "Faint Young Sun" problem? What are the alternative solutions?

3) ***For the next few decades, what can we expect in terms of extreme solar flares and storms, and also absence of activity? Another Carrington event? What is the largest solar eruption/flare possible? What is the expectation for periods with absence of activity?***

4) How does the geospace system respond to extreme events?

Some results reported at the Symposium in Israel

1. It is shown that the coronal holes are included in the overall complex surrounded by a background field

2. The classical dynamo mechanism in the bottom of the convection zone is critisaized. Arguments are given that an additional mechanism of enhancement or redistribution should in the immediate subsurface layers.

3. New approach to solar flare physics – dynamical equilibrium of 3-level percolated system

3.The very strong flares are possible at the Sun (10^{34} every 800 years, and 10^{35} every 5000 years)

4. From the analysis of young stars it was concluded that magnetic field on the young Sun was about 100 G, the activity was significantly higher

Main Questions:

1) **Are we at the verge of a new grand minimum? If not, what is the expectation for cycle 25?**

2) Does our current best understanding of the evolution of solar irradiance and mass loss resolve the "Faint Young Sun" problem? What are the alternative solutions?

3) *For the next few decades, what can we expect in terms of extreme solar flares and storms, and also absence of activity? Another Carrington event? What is the largest solar eruption/flare possible? What is the expectation for periods with absence of activity?*

4) How does the geospace system respond to extreme events?

During the VarSITI SCOSTEP meetings in Prague, it was suggested that a brain-storming meeting were organized within the framework of our SEE project to assess the future evolution of solar activity in the following decades.

It is supposed that 12-15 world leading experts would be invited to take part in this meeting. Since the other VarSITI projects also need such assessment, similar meetings are supposed to be held, where our forecast of evolution of solar activity will be used as a basis to discuss how the expected activity would manifest itself in interplanetary events, in the magnetosphere, and, finally, in the atmosphere.

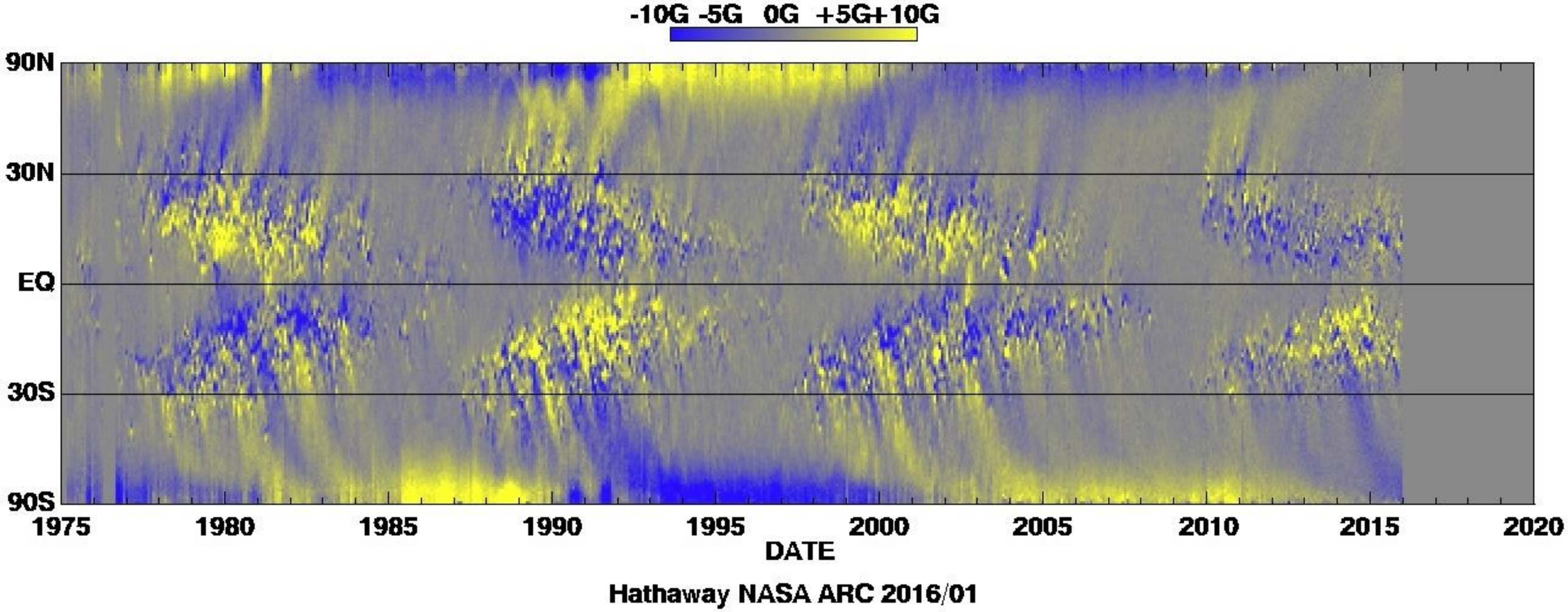
List of participants and reports

1. **Cameron, R.H.** What we know about the dynamo from observations
2. **Choudhuri, A.R.** Flux transport dynamos: from modeling irregularities to making predictions
3. **Dikpati, M.** On the refinement of dynamo-based solar cycle forecasts
4. **Georgieva, K., Kirov, B.** Flux-transport dynamo model: Constrains from geophysical data
5. **Hathaway, D.** Predicting the Amplitude and Hemispheric Asymmetry of Solar Cycle 25 with Surface Flux Transport
6. **Hiremath, K.M.** Forecast and Backcast of the Solar Cycles
7. **Jiang, J.** Observation-based random mechanisms and nonlinearities in the solar large-scale magnetic field evolution
8. **Kitiashvili, I.N.** Data Assimilation Approach to the Solar Cycle Prediction
9. **Kosovichev, A.G., Zhao, J.** Solar-Cycle Evolution of Subsurface Flows and Magnetic Fields
10. **Obridko V.N.** Some indications of the onset of a period of relatively low solar activity
11. **Passos, D.** Solar cycle predictions using a low order dynamo model
12. **Petrovay, K., Nagy, M.** Early indicators of an upcoming solar cycle at high latitudes
13. **Pevtsov, A.** How well one can predict future cycles given the stochastic nature of solar activity?
14. **Sokoloff, D.** Dynamo theory and perspectives of solar cycles forecast
15. **Stenflo, I.O.** Global aspects of solar magnetism
16. **Zharkova, V., Shepherd, S., Popova, H., Zharkov, S.** Principal components of solar magnetic field variations and predictions of solar activity on a multi-millenium timescale

Surface flux transport: Producing the polar fields

Predicting the polar fields that produce the next cycle

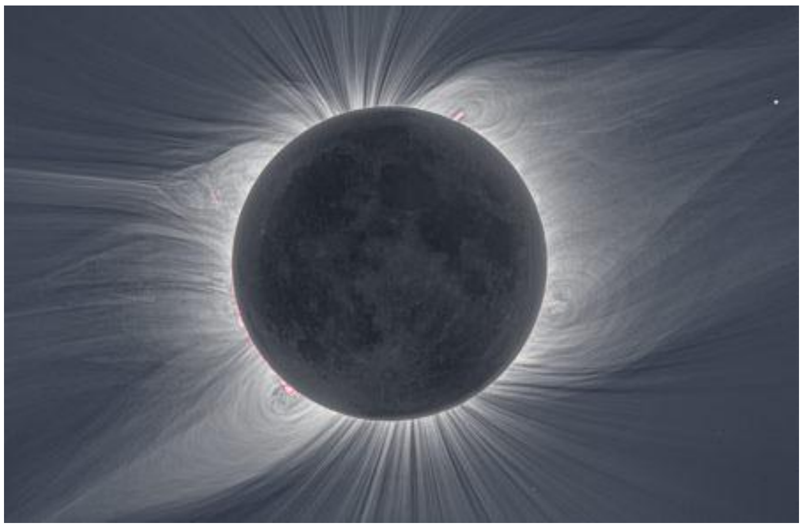
The Dynamo Observed



The radial component of the photospheric magnetic field averaged over longitude for each 27-day rotation of the Sun over the last four cycles.

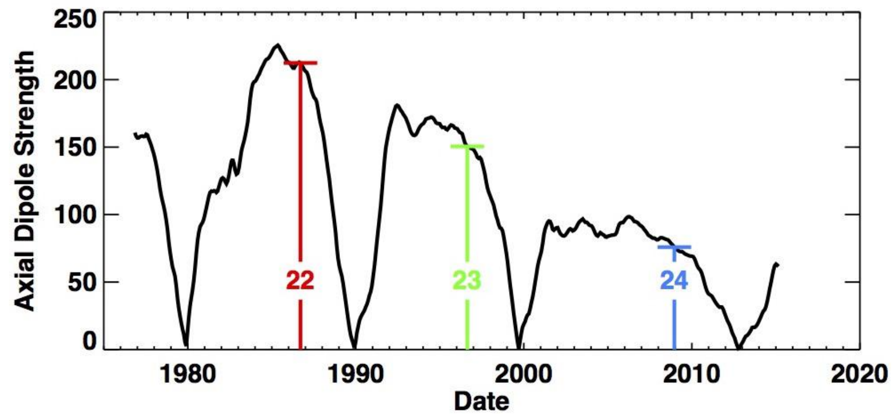
- Active latitude butterfly wings have following polarity at high latitudes and preceding polarity at low latitudes.
- Poleward transport of the predominantly following polarity flux reverses the polar fields at maximum and builds up new polar fields by the next minimum.

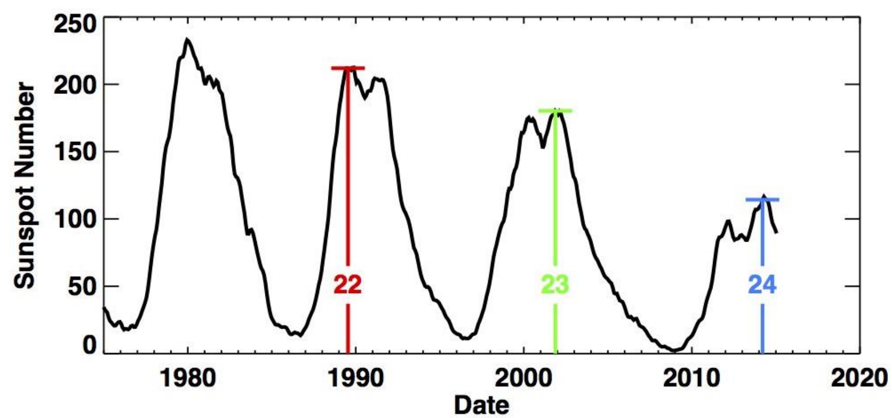
The Sun’s Magnetic Field at Minimum



August 8, 2008 Miloslav Druckmüller

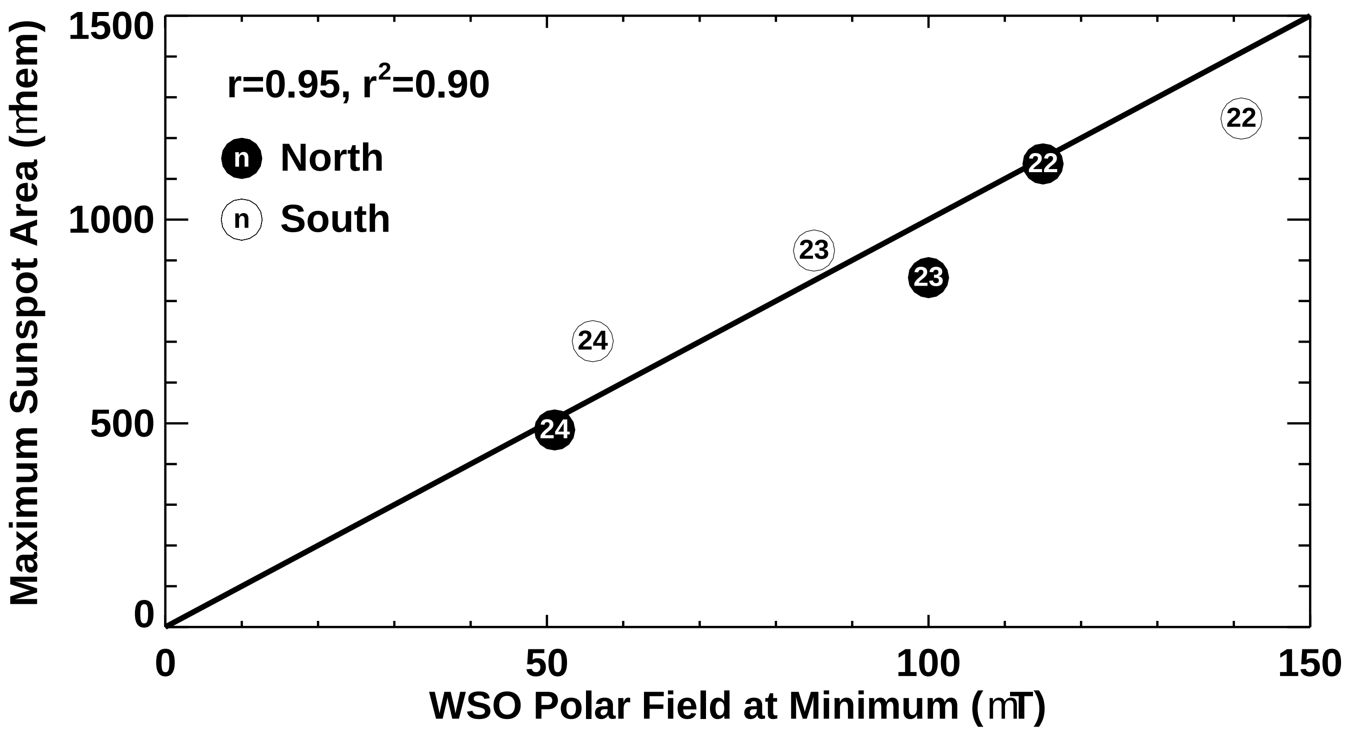
At cycle minimum the Sun’s global magnetic field is dominated by the axial dipole field. The strength of this field component near cycle minimum is well correlated with the peak amplitude of the following sunspot cycle.





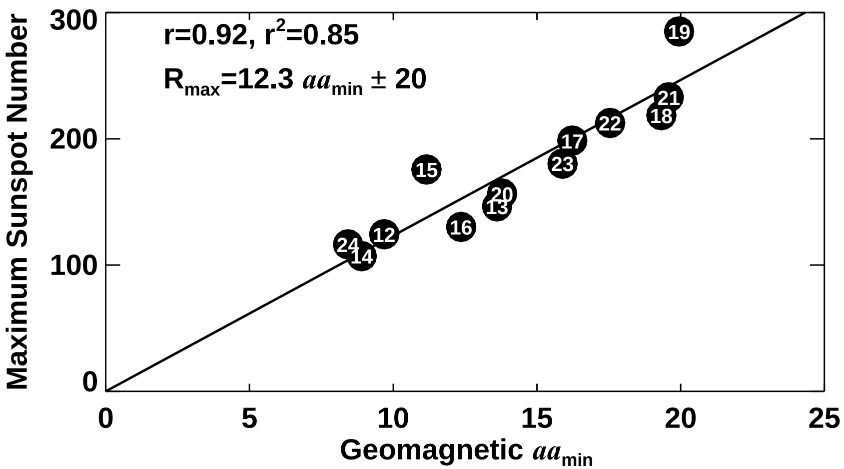
Wilcox Solar Observatory Axial Dipole Strength Measurements

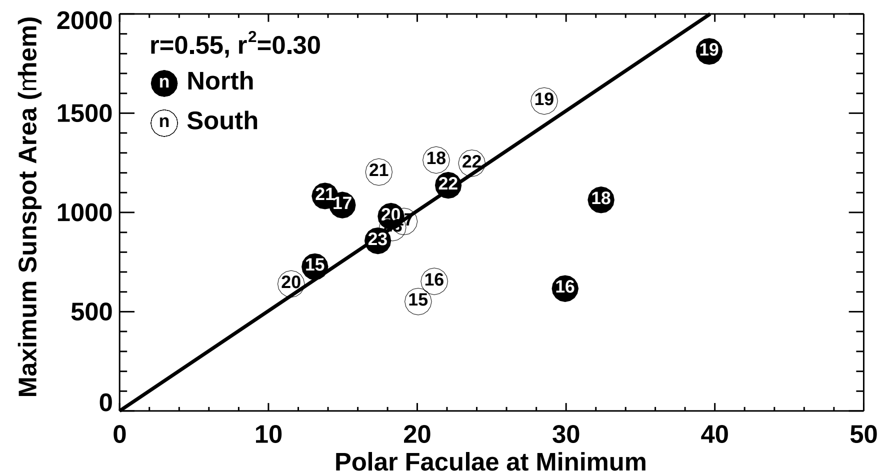
Polar Fields as Predictors



The polar field (average field strength above 55° latitude) at cycle minimum for each hemisphere is well correlated with the maximum sunspot area in the following cycle.

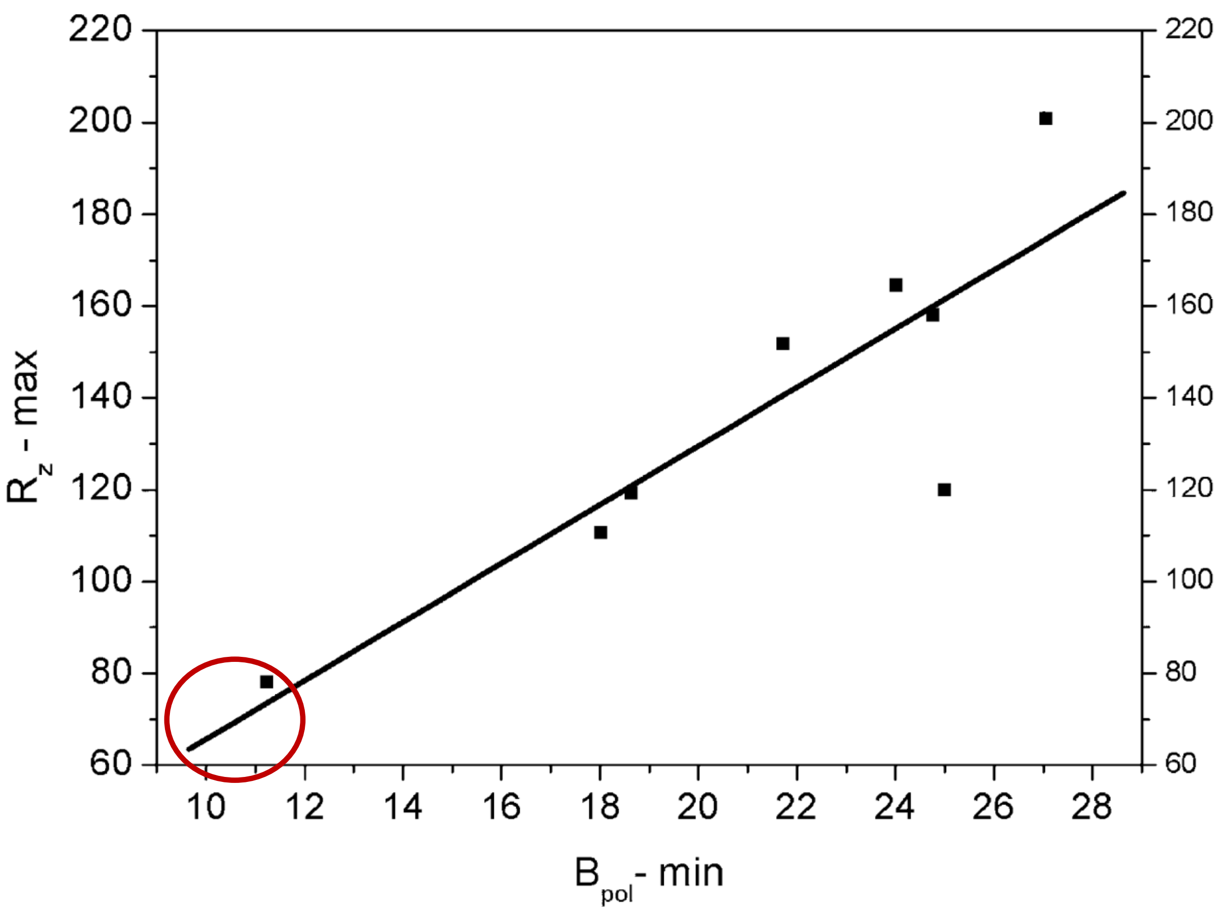
Polar Field Proxies for Earlier Cycles





The minima in the geomagnetic *aa*-Index (which occur near sunspot cycle minima) are well correlated with the maximum of the next cycle (Ohl, 1966). Wang & Sheeley (2009) argue that these minima are determined by the Sun's axial dipole strength.

Polar faculae (produced by polar magnetic elements) are also correlated with the maximum of the next cycle (Muñoz-Jaramillo et al., 2012).



Relationship between the polar magnetic field at the global field maximum and the sunspot numbers at the maximum of local fields in the forthcoming cycle. The scaling factor (0.2) was calculated for the overlapping interval of 1976 – 1990 to ensure a single data format.

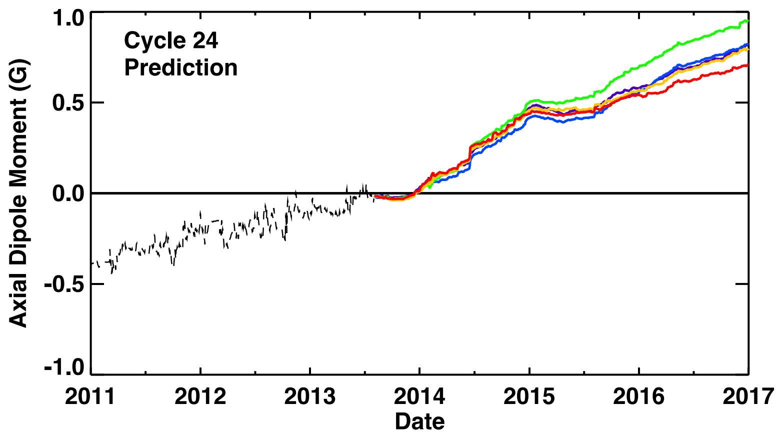
The Surface Flux Transport Promise

- The evolution of the Sun’s surface magnetic field can be obtained -

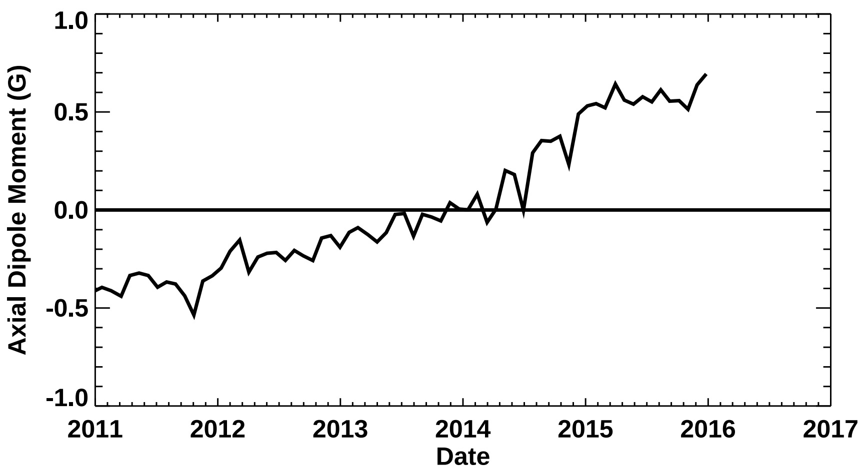
  1. **Given the emergence of (tilted) active region magnetic flux**
  2. **Given knowledge of the flows (the differential rotation, the meridional circulation, the cellular convective flows) and their variations**

- We can use surface flux transport to determine what the strength of the polar fields will be at the cycle minimum well before the end of the cycle.

Previous Prediction of Polar Fields



Our (*Upton & Hathaway, 2014*) polar field prediction based on surface flux transport using active region sources from cycle 14 (a similar cycle).

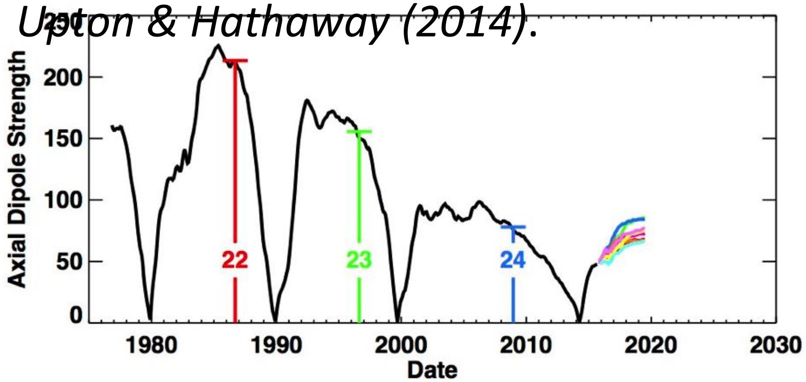


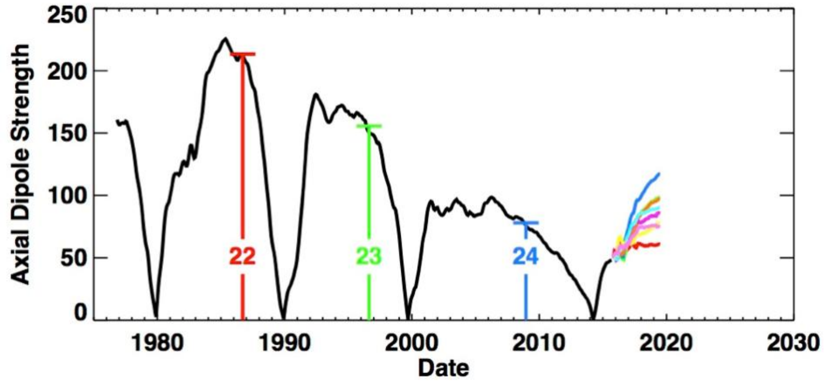
The axial dipole strength from HMI to the start of 2016 shows good agreement with our predictions from mid-2013.

Note: Using different realizations of the convective motions (multi-colored tracks) gives diverging results - e.g. axial dipole = 0.8 ± 0.1 after 3.5 years.

Predicting the Axial Dipole Strength

We use a database of sunspot group areas and positions from Cycle 14 (1901 – 1913), along with a relationship between sunspot group area and total magnetic flux, to continue adding in active region data for the rest of Cycle 24 as was done in *Upton & Hathaway (2014)*.





Eight different realizations of the convective flows (with fixed active region tilt) give slightly different field values in 2020.

Eight different realizations of the active region tilts (with the same convective realization) introduce more uncertainty in the field values in 2020.

The average of these different realizations gives an axial dipole similar (± 15%) to that preceding Cycle 24 – indicating a Cycle 25 with a peak about the same as that in Cycle 24.

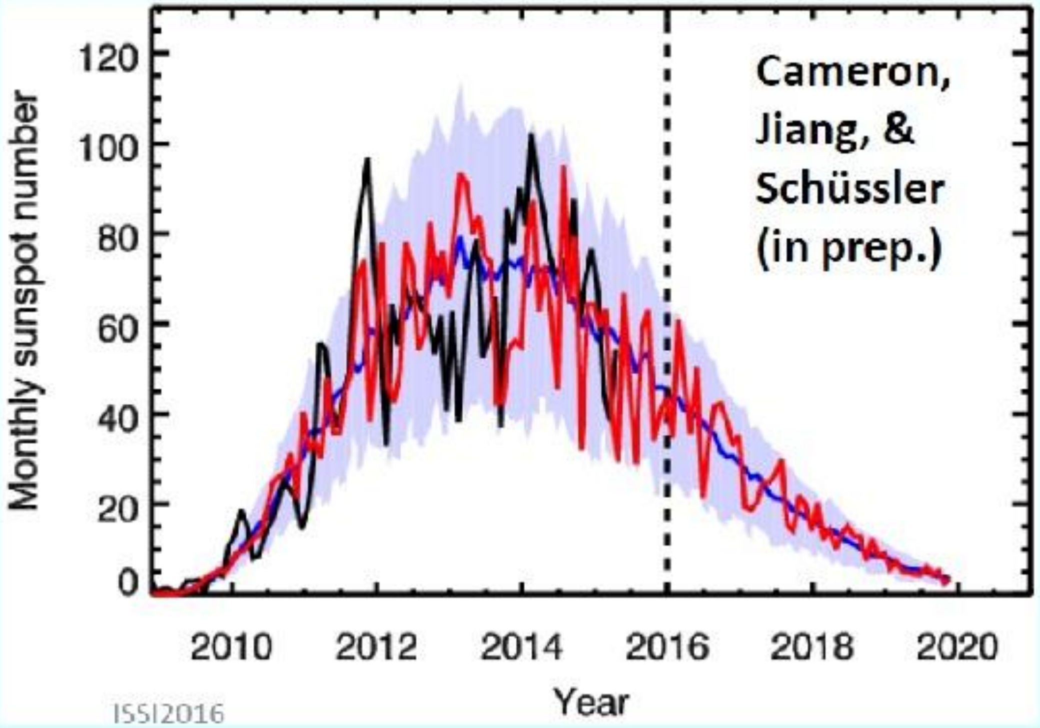
Expected amplitude of cycle 25

Time evolution of Sunspot Number during a cycle:

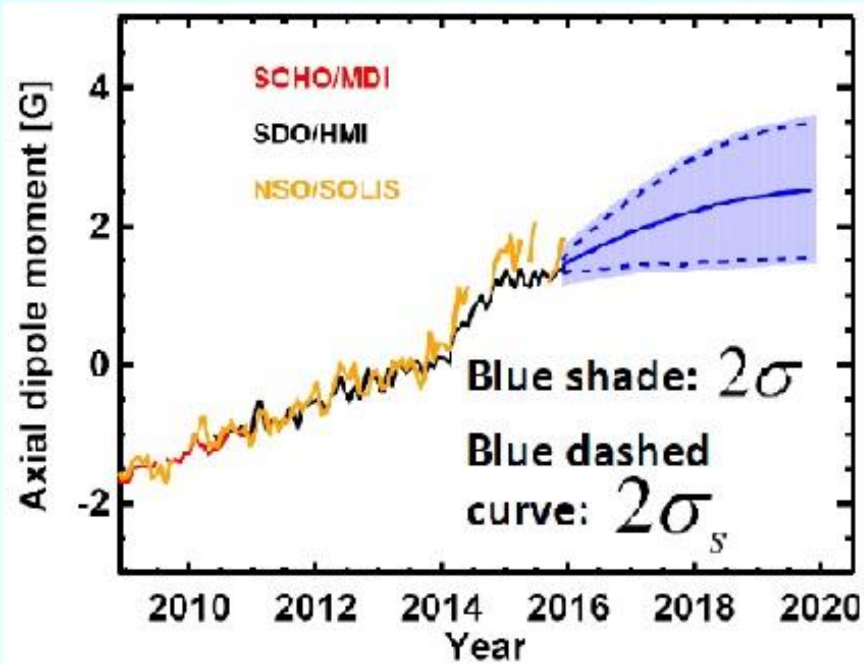
Hathaway et al. (1994): $f(t) = a(t - t_0)^3 / \{\exp[(t - t_0)^2 / b^2] - c\}$

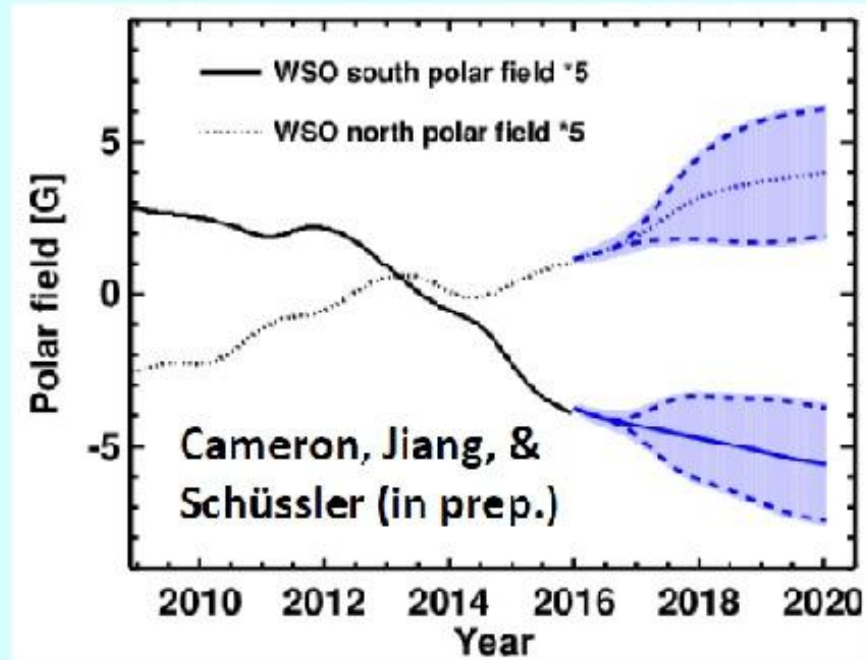
$$A(t) = f(t) + \Delta f(t), where\ \sigma_{\Delta f(t)} = 0.5 f(t)$$

- **Black cure: observed sunspot number;**
- **Red curve: one of the random realization;**
- **Blue curve: average of 50 random realizations;**
- **Light blue: 2σ of 50 random realizations**



Expected amplitude of cycle 25





- Dipole moment at 2020: 2.5±1.5G (2σ range); 2G at the end of cy.23
→ "normal" cycle 25, not grand minimum;
→ increasing error range with time: limited prediction scope

N-S asymmetry of the polar field since the reversal due to big emergences in 2014 (ARs11944 & 12192) in southern hemisphere

Conclusions

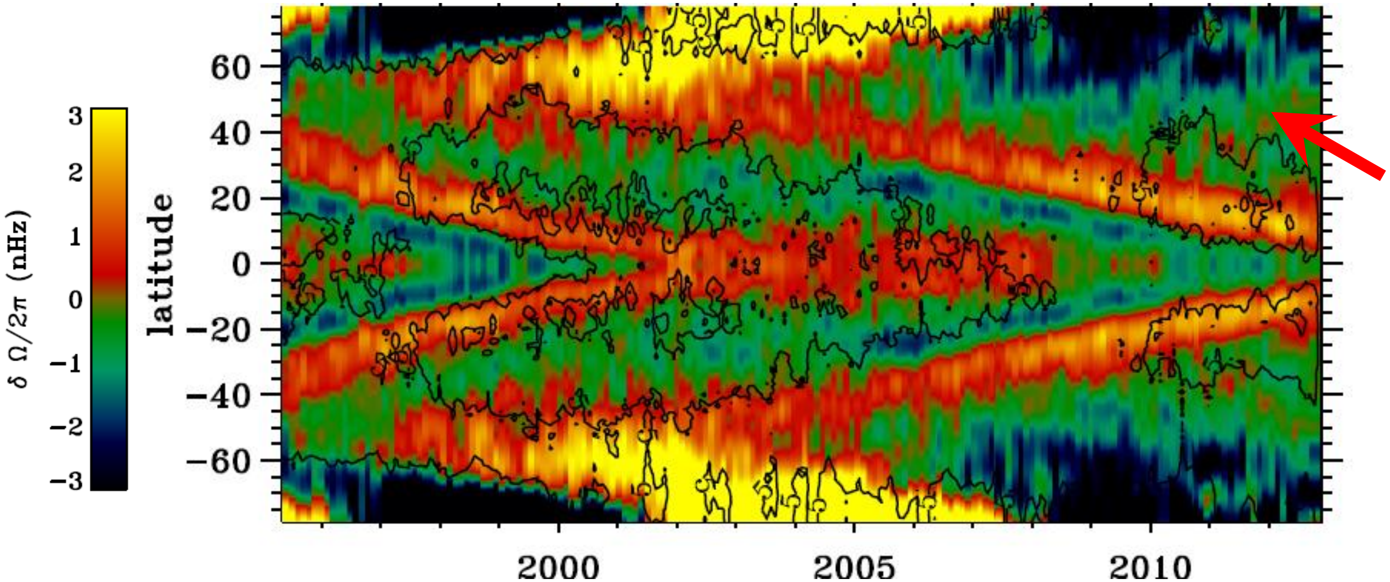
- The nonlinearities due to the cycle dependence of latitudes and tilts of sunspot groups and the stochastic effects due to the scatter in the tilts can effectively modulate cycle amplitude.

- The tilt angle scatter strongly limits the predictability of solar activity.

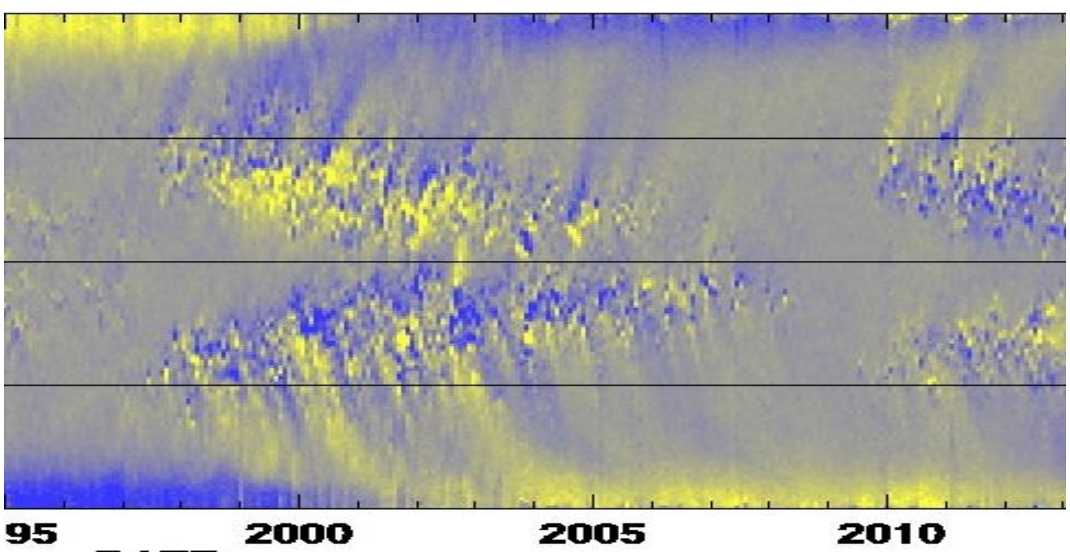
- With the nonlinearities and stochastic effects, we give our expectation of cy.25 strength with certain error range.

Solar rotation exhibits “torsional oscillations” correlated with the butterfly diagram.

However, in Cycle 24 the polar branch is missing.



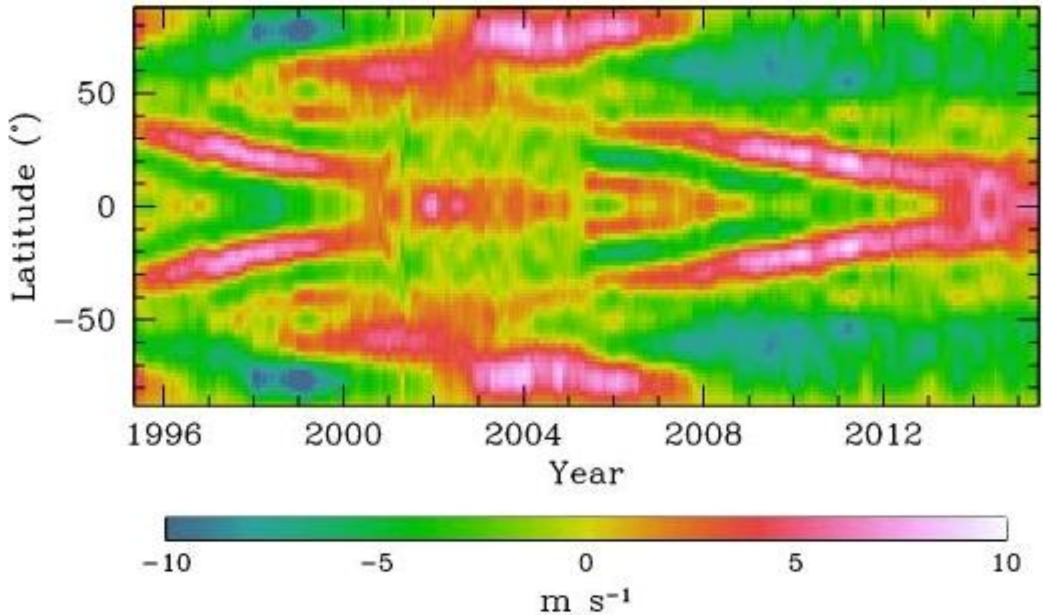
– indication of the weak Cycle 25?



Result of the global helioseismology analysis of Howe et al (2013)

Does the ‘extended solar cycle’ give us any clues for prediction?

Torsional oscillations begin at higher latitudes before the beginning of the sunspot cycle

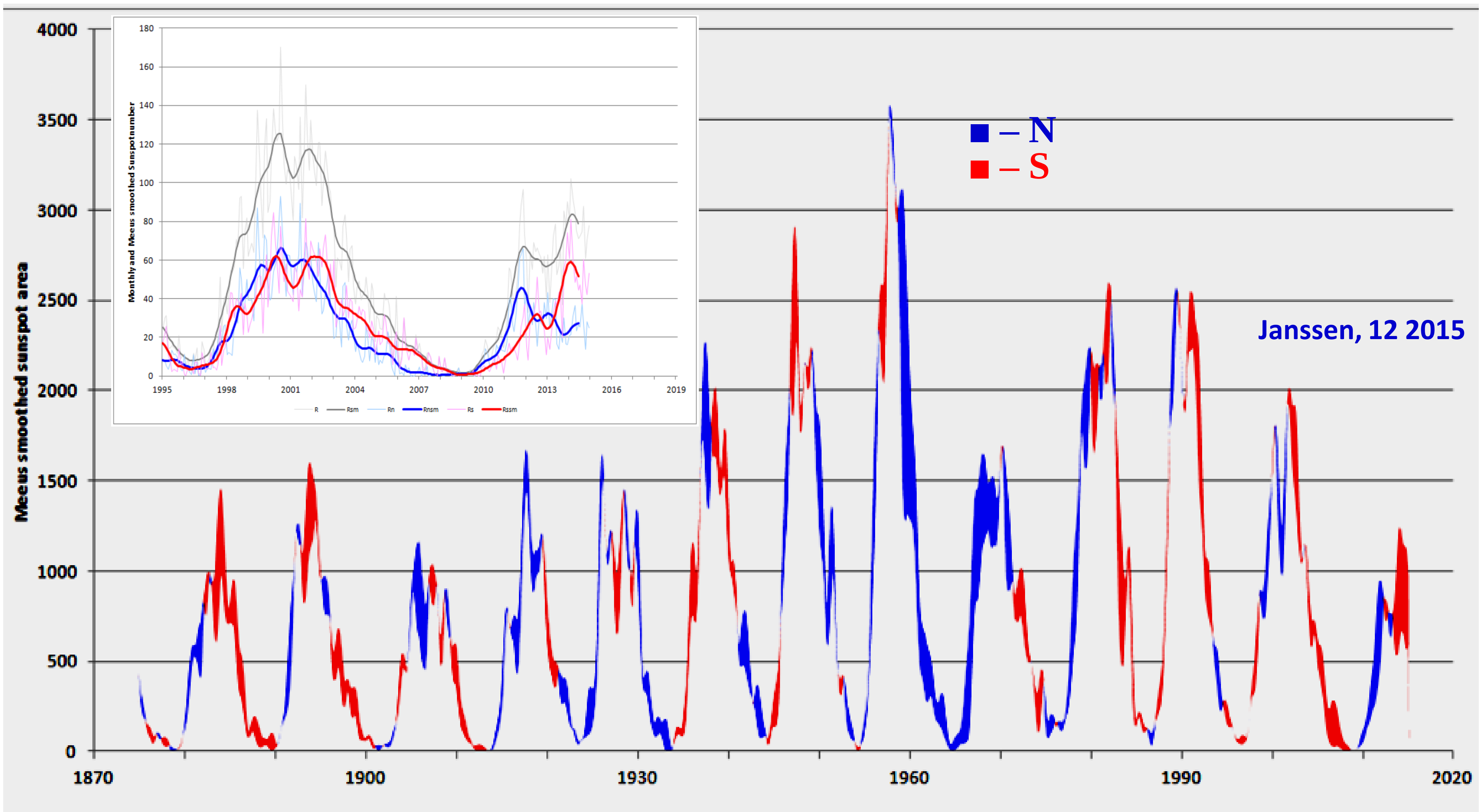


Torional oscillations at $0.98R_{\mathrm{Sun}}$ (from GONG data)

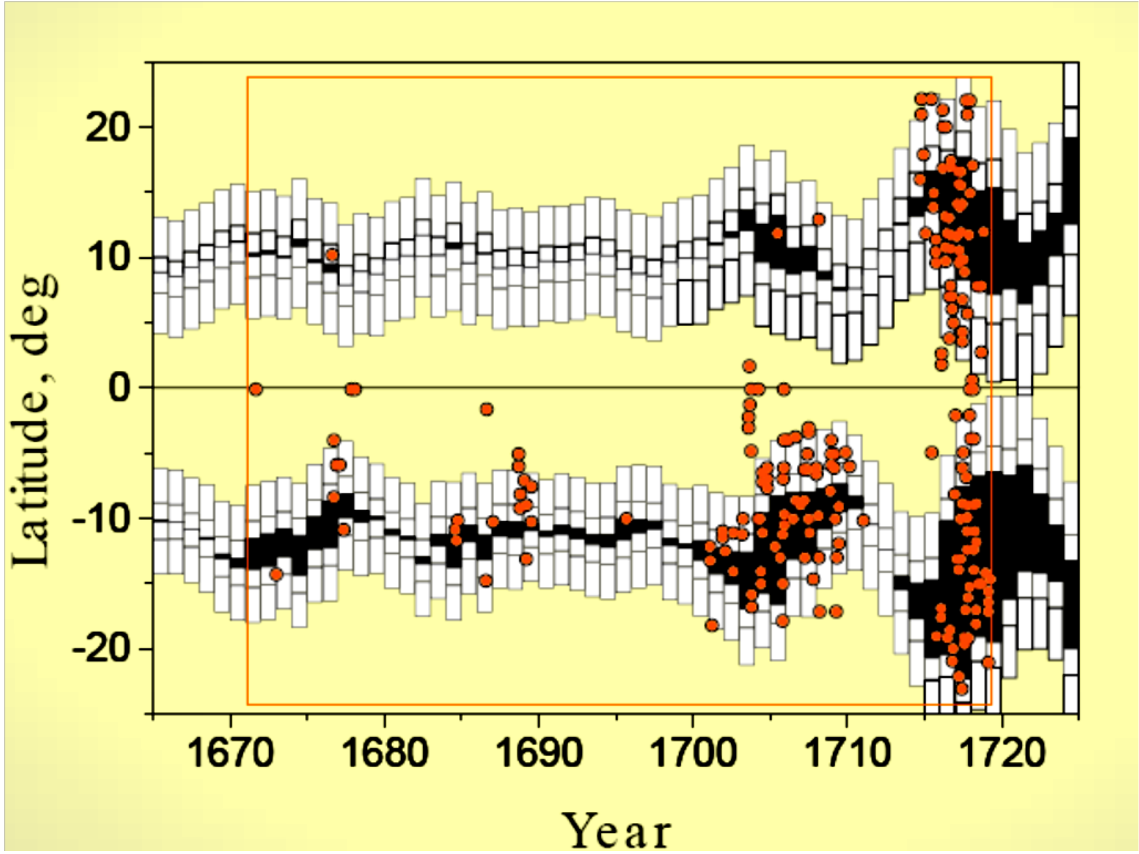
From H.M. Antia, private communication

Oscillations for cycle 25 have not started yet!!!
What does it imply?

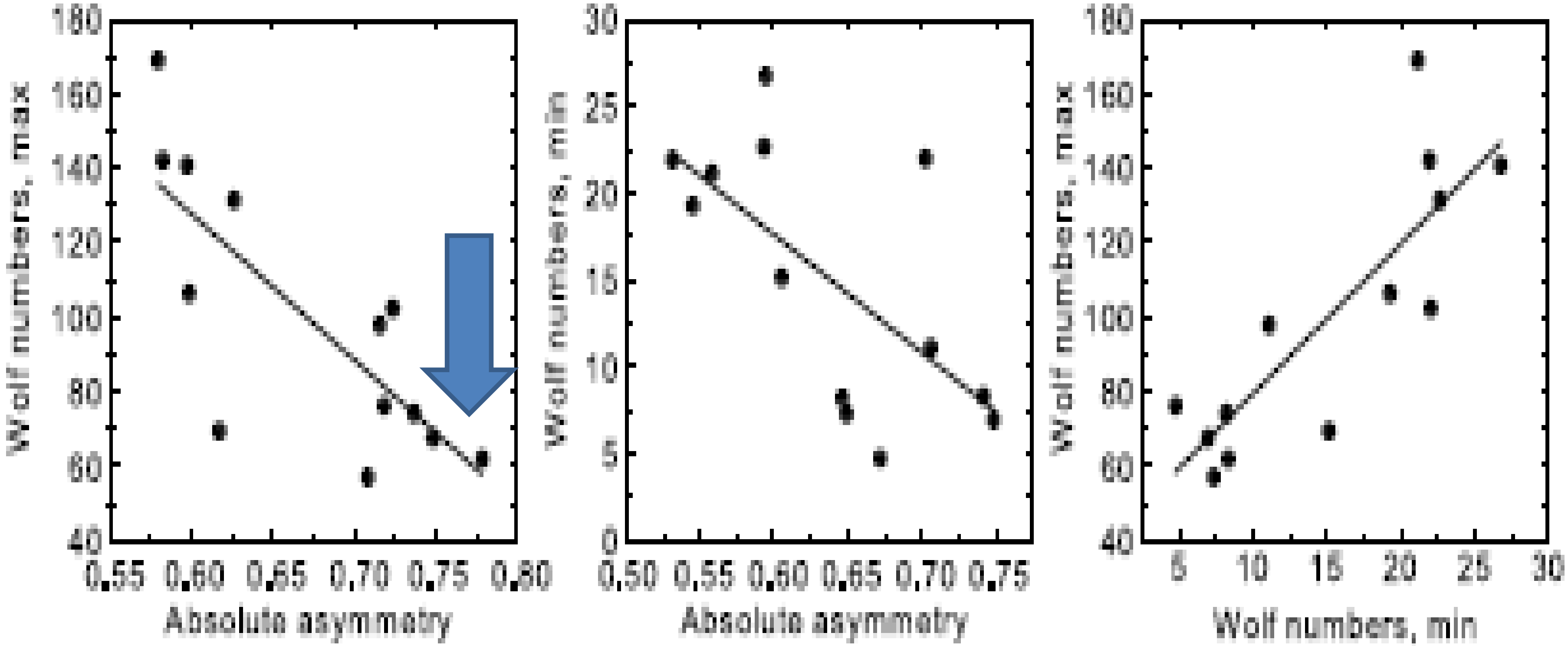
Since 2013, we have observed a strong asymmetry in the occurrence of sunspots in favor of the southern hemisphere, with the first maximum ensured by sunspot groups of the northern hemisphere and the main one, by sunspot groups of the southern hemisphere.



North-South asymmetry in the occurrence of sunspots , mean sunspot latitudes, and «butterfly diagram» during the Maunder minimum



Model Maunder butterflies for the period of the global minimum of solar activity (dark areas) and their comparison with observations for 1671–1718 (circles). The vertical rectangles show the *σ*- and 3*σ*-confidence intervals of the model in latitude.



- Left – correlation between the value of asymmetry at the cycle
- minimum and the height of maximum of the following cycle; center –
- correlation between the asymmetry modulus and the Wolf numbers at
- the minimum of the cycle; right – correlation between theWolf numbers
- minimum and the following maximum.

Flux Transport dynamo

(Choudhuri, Schussler & Dikpati 1995)

High diffusivity model

(diffusion time ~ 5 yrs)

IISc group

(Choudhuri, Nandy, Chatterjee, Jiang, Karak)

Low diffusivity model

(diffusion time ~ 200 yrs)

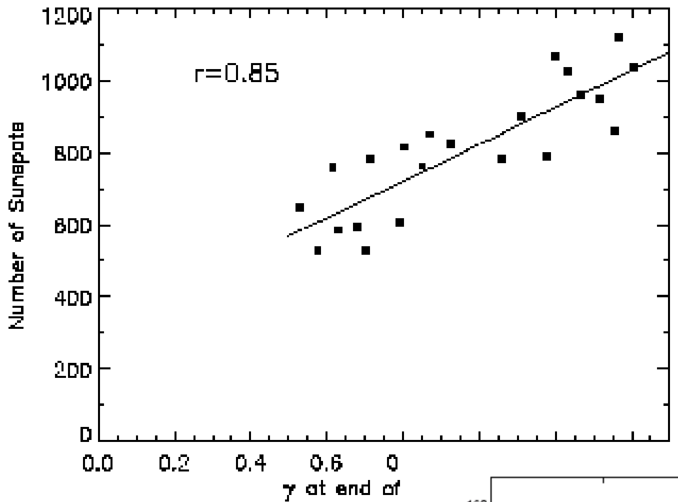
HAO group

(Dikpati, Charbonneau, Gilman, de Toma)

Differences between these models were systematically studied by Jiang, Chatterjee & Choudhuri (2007) and Yeates, Nandy & Mckay (2008)

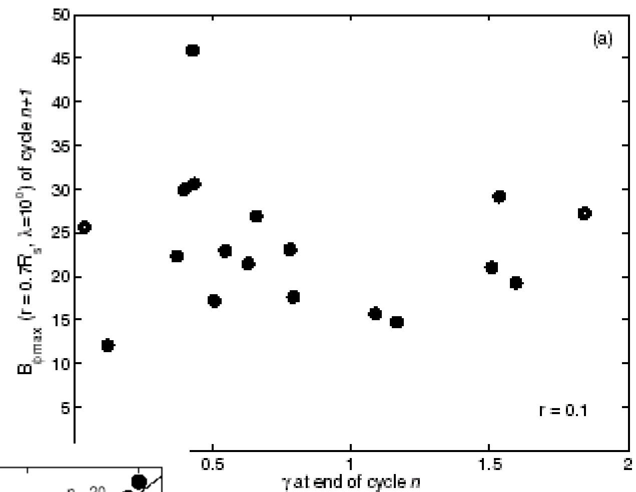
Downward turbulent pumping also mimics high diffusivity (Karak & Nandy 2011)

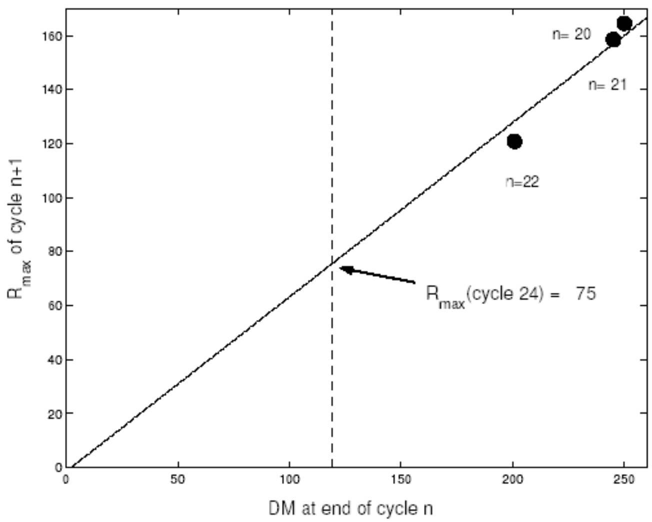
Correlations seen in numerical simulations with random kicks at the sunspot minima (from Jiang, Chatterjee & Choudhuri 2007)



High diffusivity

(our model)

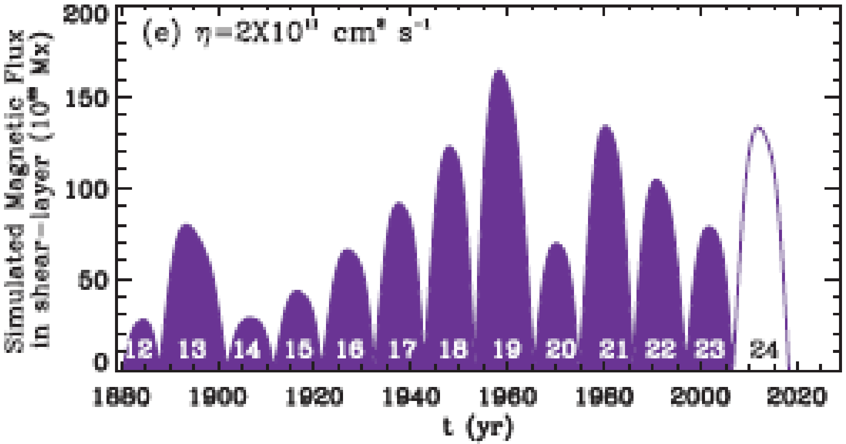


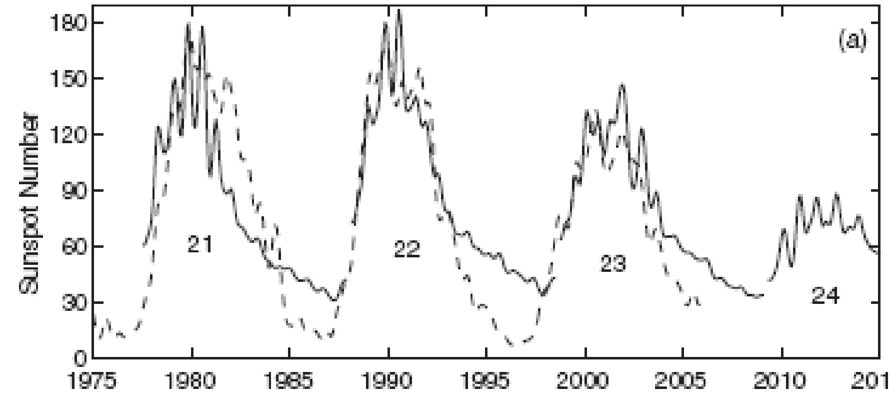


Low diffusivity

(Dikpati-Gilman)

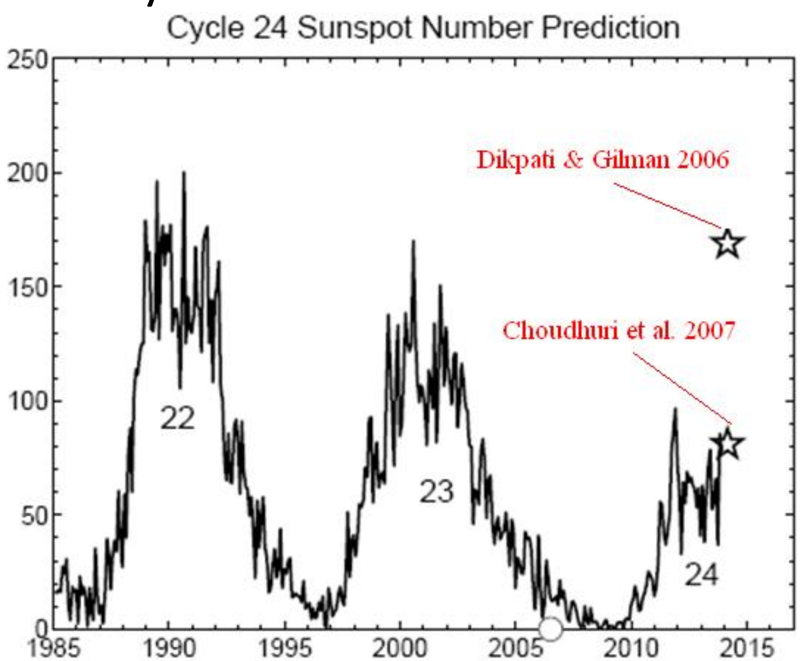
Prediction of Solar Cycle 24





Dikpati & Gilman (2006) – low diffusivity model

Choudhuri, Chatterjee & Jiang (2007) – high diffusivity model



The long memory of the low-diffusivity model would make meaningful predictions impossible!

Possible causes of solar cycle irregularities

- Effects of nonlinearities **(some evidence for it)**
- Fluctuations in poloidal field generation **(needed to explain correlation between polar field & strength of next cycle)**
- Fluctuations in meridional circulation **(needed to explain Waldmeier effect)**

High-diffusivity model is preferred!

What causes grand minima?

Early suggestion was nonlinear chaos (Weiss, Cattaneo & Jones 1984; Beer, Tobias & Weiss 1998)

Large fluctuations in poloidal field generation can cause intermittencies like grand minima (Choudhuri 1992; Moss et al. 1992; Hoyng 1993; Charboneau, Blais-Laurier & St-Jean 2004)

Grand minima in flux transport dynamos caused jointly by fluctuations in Babcock-Leighton mechanism and meridional circulation

Conclusions

- For prediction of the next cycle it is very important to predict the poloidal field. There is a progress in this direction.
- The main sources of cycle irregularities (including grand minima) are fluctuations in poloidal field generation and fluctuations in meridional circulation (with nonlinear chaos also probably making some contribution)
- Kinematic flux transport dynamo models with high diffusivity can explain many aspects of the solar cycle
- We need to assimilate data to incorporate these fluctuations in theoretical dynamo models in order to model past cycles and predict a future cycle

- Thus, in general, one may expect the beginning of the 21st century to be characterized by one or two cycles with a fairly low or just low intensity. A more serious, Maunder-type decline of activity or at least the decline that was observed at the beginning of the 20th century cannot be ruled out either.

Resume

- In the next few decades, solar activity will correspond to the average (more likely) or the type of Dalton minimum (less likely).

Thank You for Attention!