Towards Coupling Forecasting Methods and Numerical Simulations to Improve our Understanding of Solar Magnetism and Activity

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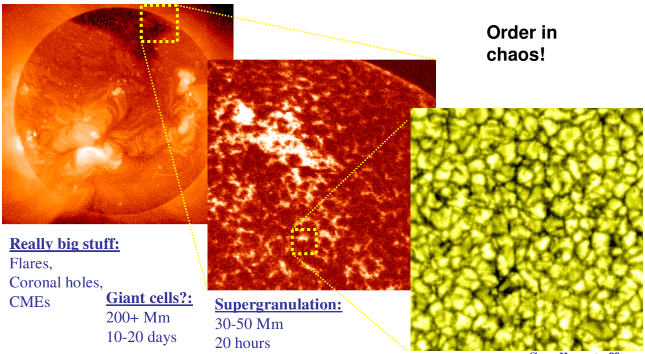
- Observational properties
- Model of the solar convection zone and magnetism
- Prediction vs physical modelling

Solar Convection Scales



Order in chaos!

Really big stuff:
Flares,
Coronal holes,
CMEs

Giant cells?:
200+ Mm
10-20 days

Supergranulation:
30-50 Mm
20 hours

Mesogranulation?:
7-10 Mm
2 hours

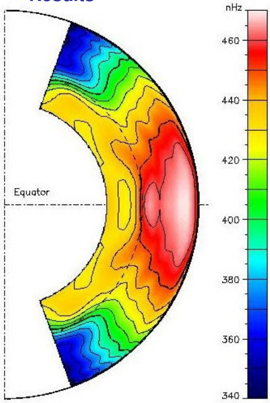
Granulation:
1-2 Mm
5 mins

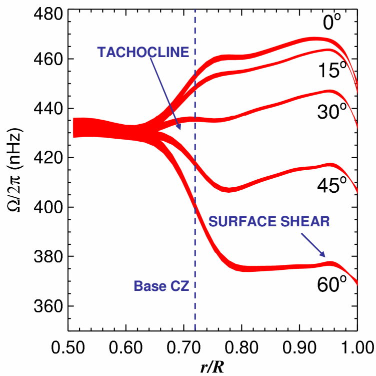
Smaller stuff:
Intergranular lanes,
magnetic bright
points, diffusion

Solar Internal Rotation

Helioseismology Results

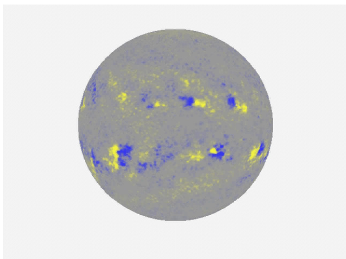
(GONG, MDI data)





Main Properties of the Solar Magnetism/Dynamo

1. An activity cycle of 22 yr
2. Small and Large scale dynamos
3. Butterfly diagram (Sporer's law) of the toroidal field within a latitudinal band of +/- 30 deg
4. Tilt of 4 to 10 deg of bipolar regions (Joy's law), opposite polarity between northern and southern hemisphere for "leading spot" (Hale's law)
5. Poloidal field migrating from mid latitudes towards the poles
6. 90 deg phase shift between polar surface field and deep toroidal field, such that the polar field reverses (- -> +) when Btor is at maximum strength (+)
7. Btor ~ 10^4-10^5 G in tachocline
8. Bpol ~ 10 G at poles (surface amplitude)



Maunder Minimum (~1650-1715)

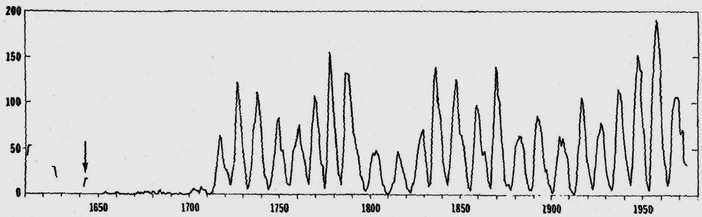


Fig. 1. Annual mean sunspot numbers, A.D. 1610–1974, from Waldmeier (1961) and Eddy (1976). Arrow marks the period of this study, 1642–1644.

(Eddy et al 1976)

The Puzzling Dynamical Sun:

- Questions: what are the processes at the origin of the solar cycle, activity and dynamical behavior (turbulent convection, solar cycle, magnetic activity, differential rotation, MC flow,…)?
- How to get ready to the high data flow of SDO and other experiments that deliver high resolution (both spatially and temporally) data of the solar dynamics?

- 2 possible approaches:

1) model using/assimilating data in order to be able to predict and anticipate the evolution of the dynamical system , agreement with obs data is key
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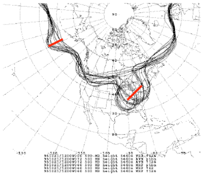
The Point of View of Climate/Weather Forecasting

Error Evolution is Key

This is an example of "spaghetti" plots showing a very unpredictable storm, with large uncertainties after only 2.5 days. Note that for this case the uncertainties lie essentially within one degree of freedom (red lines). This low dimensionality in the "errors of the day" makes possible adaptive observations and Ensemble Kalman Filter

The atmosphere is chaotic: The present determines the future, but the approximate present does not determine the approximate future (Lorenz, 2006!!!)

- The atmospheric predictability depends on the "errors of the day" (and month, season).
- They are instabilities of the atmosphere
- They make small errors grow fast
- We now deal with chaos by doing ensemble forecasting
- We perturb the initial conditions and/or the model and run an ensemble of forecasts.
- Spaghetti plots show a single contour line for each of the forecasts, thus showing the regions of agreement and where there is large uncertainty (errors of the day)



2.5-days ensemble prediction

The Point of View of Climate/Weather Forecasting

Sensitivity to initial conditions:

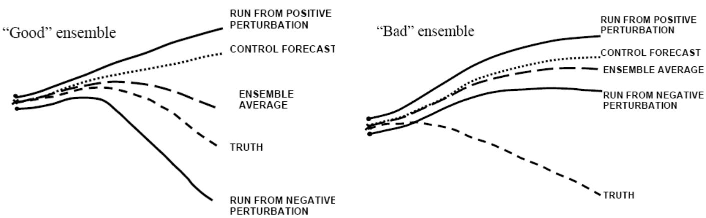
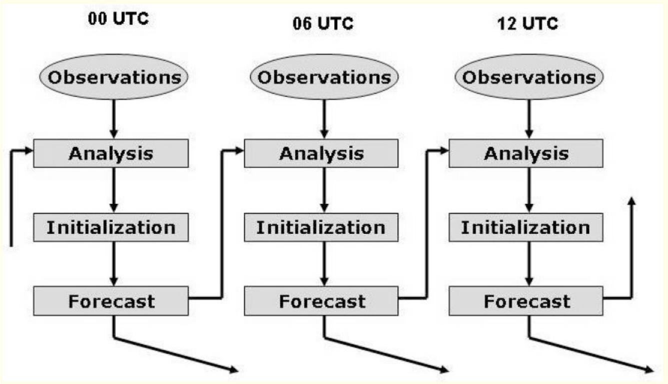


Figure 1: Schematic of the essential components of an ensemble of forecasts: The analysis (denoted by a cross) constitutes the initial condition for the control forecast (dotted); two initial perturbations (dots around the analysis), chosen in this case to be equal and opposite; the perturbed forecasts (full line); the ensemble average (long dashes); and the verifying analysis or truth (dashed). The first schematic is a "good ensemble" in which the truth is a plausible member of the ensemble. The second is an example of a bad ensemble, quite different from the truth, pointing to the presence of deficiencies in *the forecasting system* (in the analysis, in the ensemble perturbations and/or in the model).

Talagrand 1997,
Kalnay et al. 1999

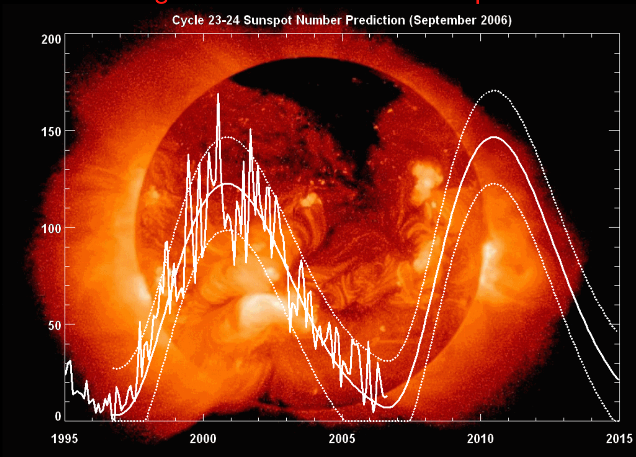
Current Data Assimilation Procedure in Weather Forecast



Typical 6-hour analysis cycle.

Lynch 2005, Kalnay 2002

Forecasting in the Solar Case: Sunspot number



NASA/MSFC/Hathaway

A synthesis of solar cycle prediction techniques

David H. Hathaway, Robert M. Wilson, and Edwin J. Reichmann
NASA Marshall Space Flight Center, Huntsville, Alabama

Abstract. A number of techniques currently in use for predicting solar activity on a solar cycle timescale are tested with historical data. Some techniques, e.g., regression and curve fitting, work well as solar activity approaches maximum and provide a month-by-month description of future activity, while others, e.g., geomagnetic precursors, work well near solar minimum but only provide an estimate of the amplitude of the cycle. A synthesis of different techniques is shown to provide a more accurate and useful forecast of solar cycle activity levels. A combination of two uncorrelated geomagnetic precursor techniques provides a more accurate prediction for the amplitude of a solar activity cycle at a time well before activity minimum. This combined precursor method gives a smoothed sunspot number maximum of 154 ± 21 at the 95% level of confidence for the next cycle maximum. A mathematical function dependent on the time of cycle initiation and the cycle amplitude is used to describe the level of solar activity month by month for the

Hathaway et al. 1999, 2004

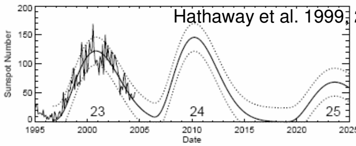


Figure 10. Predicted sunspot numbers using sunspot cycle characteristics. Predicted values are shown by the thick smooth curve. The dotted curves indicate the expected range of variation. The jagged line shows the monthly averaged International Sunspot Numbers. The drift rate of the sunspot area centroids indicate a large cycle for cycle 24 and a small cycle for cycle 25. These amplitudes in turn indicate a short cycle for cycle 23 and a long cycle for cycle 24.

Nature 2006

THE DARK SIDE OF THE SUN

The Sun occasionally hurls streams of particles towards Earth, where they can wreak havoc with satellites. Predicting these solar storms is hard, but some physicists believe we're about to face the biggest bout of solar flares in years. **Stuart Clark** reports.

Predicting the timing and strength of such solar eruptions is clearly important, but it is hampered by the fact that scientists know relatively little about the Sun's inner workings. So to coincide with the start of the next solar cycle, the largest coordinated study of the Sun will be launched next year. Known as the International Heliophysical Year (IHY), the initiative hopes to build awareness of the Sun's possible influence on Earth's climate and to bring researchers from different disciplines together to study solar activity.

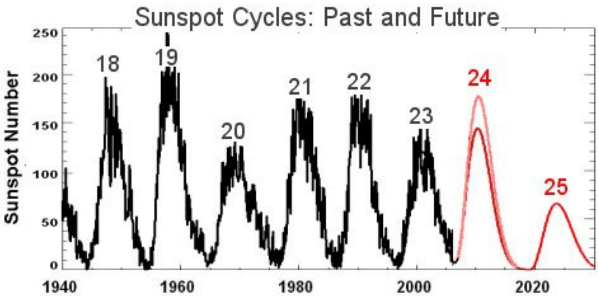
Gilman & Dikpati vs Svalgaard

sobering conclusion. "We expect between 30% and 50% more sunspots and solar activity than the cycle just ending," says Gilman, who is a member of Dikpati's team.

=> Strong correlation with cycle n-2

the previous solar cycle immediately kicks off the activity of the next. "It is good for science that the predictions are now diverging," says Svalgaard,

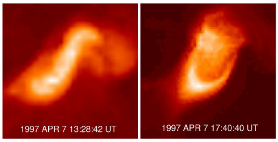
=> Use cycle n-1



Hathaway disagrees with one point. Dikpati's forecast puts Solar Max at 2012. Hathaway believes it will arrive sooner, in 2010 or 2011. "History shows that big sunspot cycles 'ramp up' faster than small ones," he says.

Forecasting in the Solar Case: CME's

CMEs and Sigmoid Features



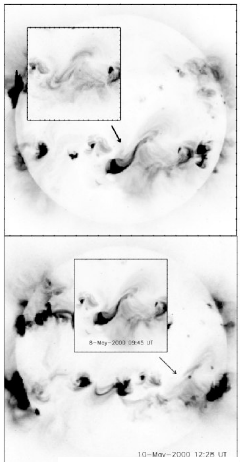
1. Sigmoid structures are often seen in Soft X-Rays (SXRs) prior to the onset of CMEs.
2. They are more apparent in SXT (SXR) than EIT (EUV) images (hotter features).
3. Regions sigmoid prior to the eruption evolve into un-sheared arcades or cusp after the eruption.
4. The position of the footpoints changes after the eruption.
5. Dimming regions associated with the sigmoid-feature eruptions are seen in and the associated mass is an order of magnitude (or more) less than of a typical CME.

Key Questions

1. Not all front-side CMEs are associated with sigmoids or other SXR event.
2. It is still not possible to know if a sigmoid is going to produce a CME or not. Or when it is going to erupt.
3. Another outstanding question is whether the sigmoid regions are sources for the entire CME, or only for one portion of the structure.

The Process

1. The magnetic field stores energy via helicity, producing S-shaped loops called a *sigmoid*.
2. At some point, this sigmoid becomes unstable and erupts. Losing some of its complexity or even disappearing completely.



L. Carcedo, A. W. Hood, D. S. Brown

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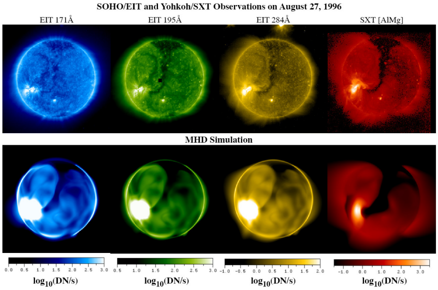
Forecasting in the Solar Case: Coronal Holes

Quantitative Comparison Between Observed and Computed Coronal Emission

SOHO/EIT and Yohkoh/SXT Observations on August 27, 1996



Mikic et al. 2006 (Whole Month Sun 3)

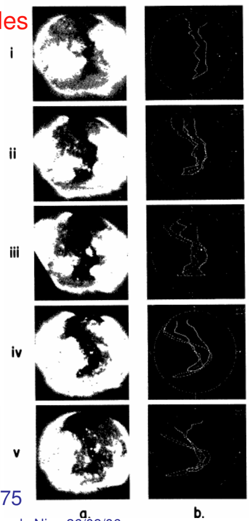


Fig. 9. Comparison of the position of CH1 as seen (a) in soft X-ray wavelengths 3–32 Å and 44–54 Å and (b) its extrapolated position calculated using the Newton and Nunn (1951) differential sunspot rotation rates. Images are shown in five successive rotations for: (i) June 1, 1973; (ii) June 28, 1973; (iii) July 25, 1973; (iv) August 21, 1973; and (v) September 28, 1973. The solid line on each schematic represents the outline of the hole as measured on that rotation, the dotted line shows the extrapolated position of the hole measured on the first rotation and rotated through the appropriate time interval.

Timothy et al. 1975

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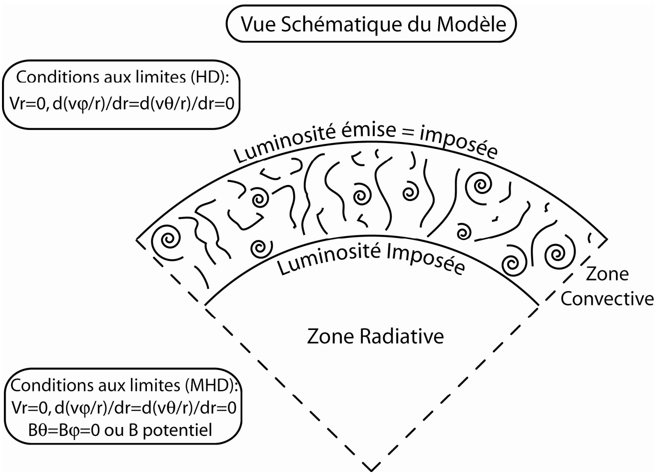
Modelling the Global Solar Magnetohydrodynamics



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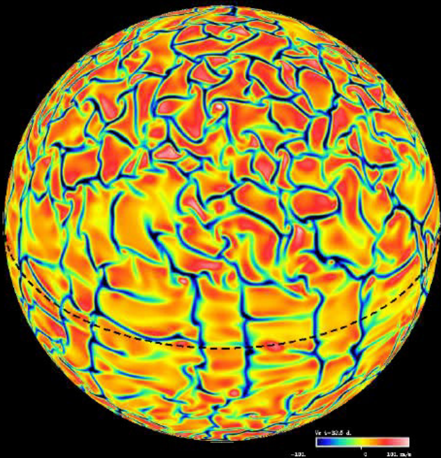
Convective Motions (radial velocity v_r)

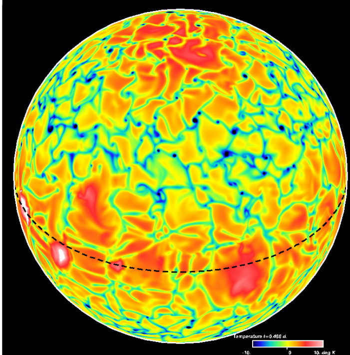
Resolution~ 1000^3
Re=VrmsD/ν~800
Pr=0.25

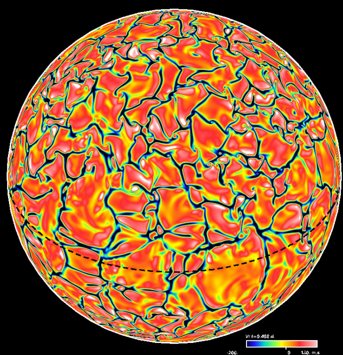
depth=0.96 R

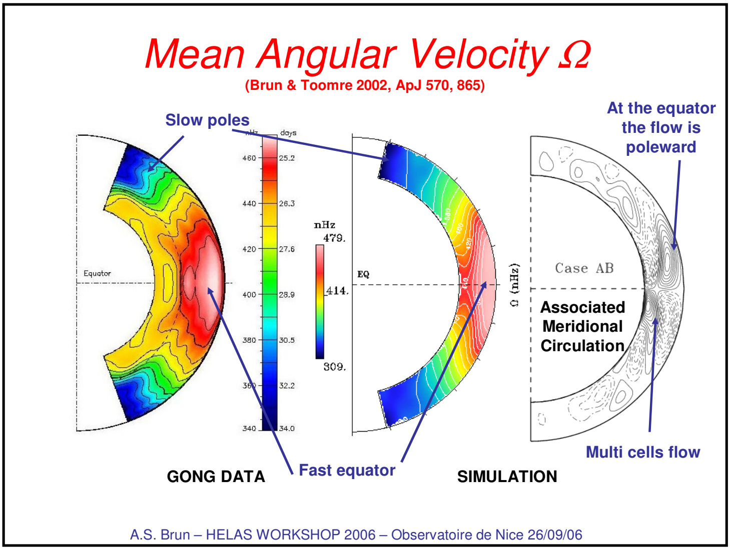


(Brun & Toomre, 2002, ApJ, 570, 865)

Temperature/Radial Velocity Correlations in Turbulent Convective Flows






Mean Angular Velocity Ω
(Brun & Toomre 2002, ApJ 570, 865)
Slow poles
At the equator the flow is poleward
Case AB
Associated Meridional Circulation
Multi cells flow
GONG DATA
Fast equator
SIMULATION
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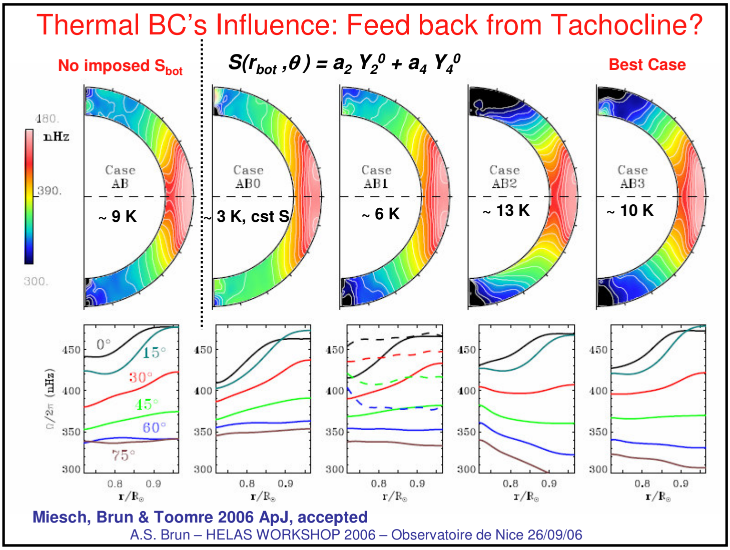
Thermal BC's Influence: Feed back from Tachocline?
No imposed S_bot
S(r_bot, θ) = a_2 Y_2^0 + a_4 Y_4^0
Best Case
Case AB
~ 9 K
Case AB0
~ 3 K, cst S
Case AB1
~ 6 K
Case AB2
~ 13 K
Case AB3
~ 10 K
Miesch, Brun & Toomre 2006 ApJ, accepted
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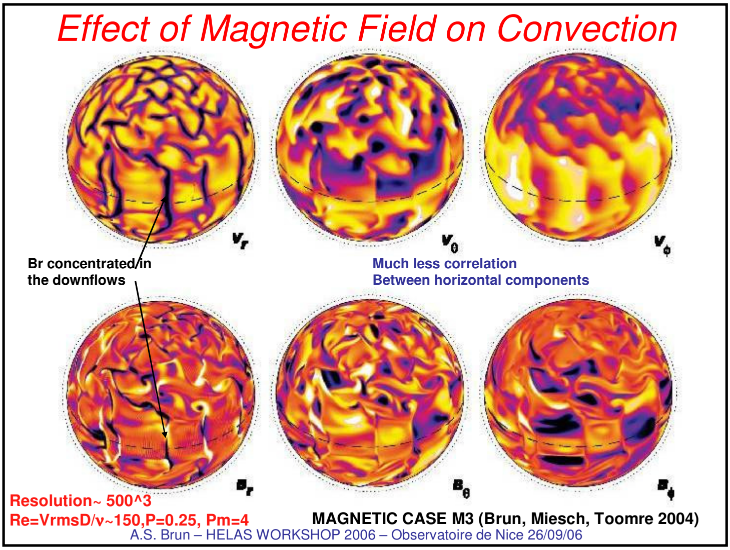
Effect of Magnetic Field on Convection
v_r
v_θ
v_ϕ
Br concentrated in the downflows
Much less correlation
Between horizontal components
B_r
B_θ
B_ϕ
Resolution~ 500^3
Re=VrmsD/ν~150,P=0.25, Pm=4
MAGNETIC CASE M3 (Brun, Miesch, Toomre 2004)
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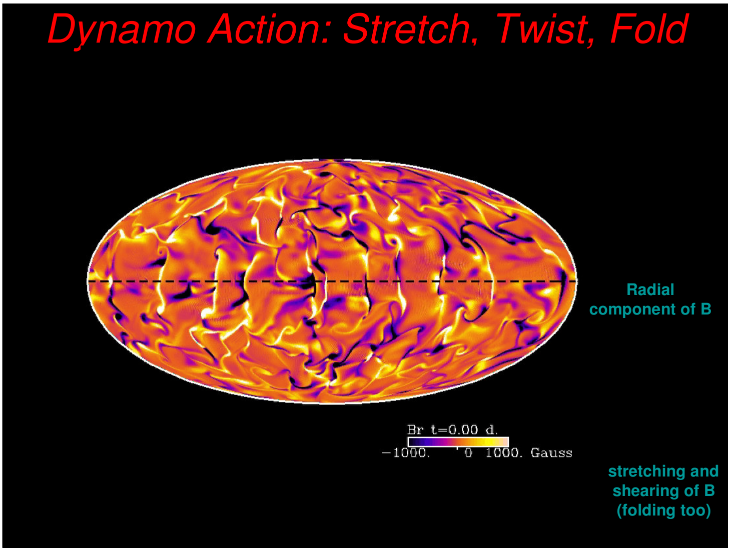
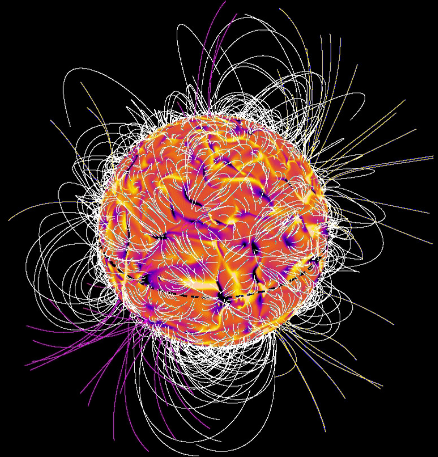

Dynamo Action: Stretch, Twist, Fold
Radial component of B
Br t=0.00 d.
−1000. 0 1000. Gauss
stretching and shearing of B (folding too)

3-D Reconstruction of the Coronal Field

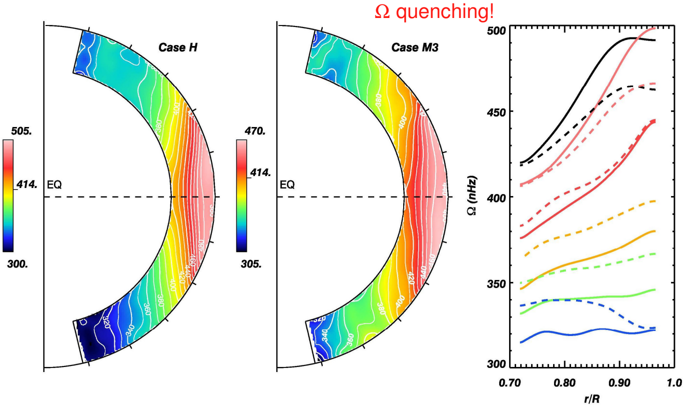


case M3

(Brun et al., ApJ, 2004)

Mean Angular Velocity Ω

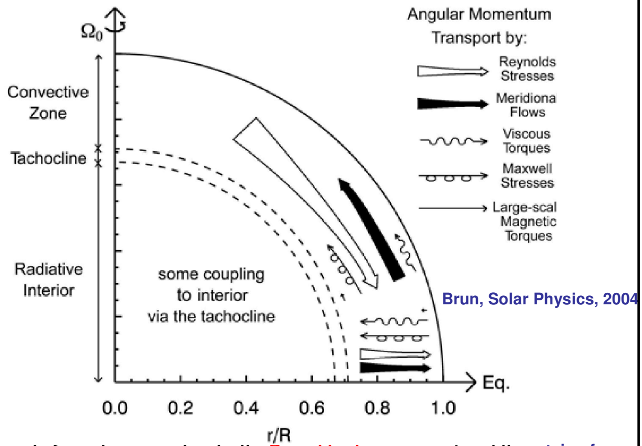
Ω quenching!



Initial state of differential rotation

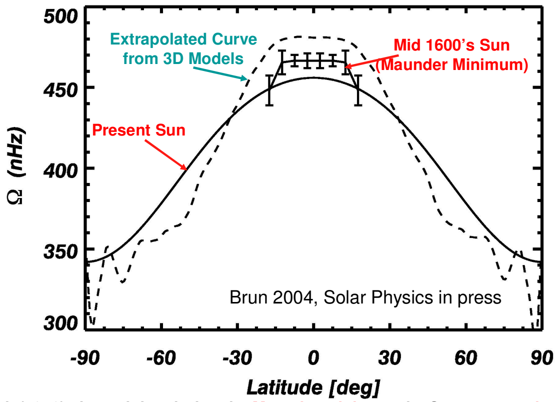
Evolved state of differential rotation under the influence of the Lorentz force

Angular Momentum Balance in Presence of B



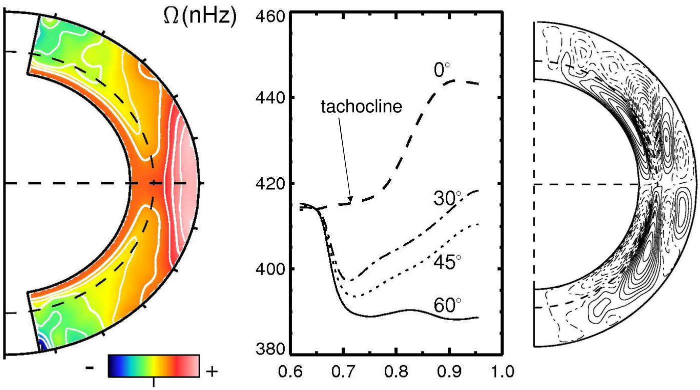
The transport of angular momentum by the Reynolds stresses remains at the origin of the equatorial acceleration. The Maxwell stresses seeks to speed up the poles.

Predicting Solar Rotation Profile during Maunder Min



- **Eddy et al. (1976) showed that during the Maunder minimum the Sun was rotating 4% faster than today**
- A Magnetic energy of about 5-7% of the kinetic energy gives the correct slowing down

Influence of a Tachocline



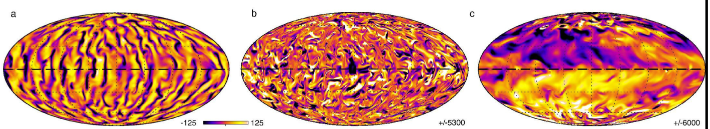
We impose a thermal wind in the stable lower zone compatible with a tachocline of shear maintained by a viscous drag.

Browning et al. 2006, ApJL, 648

Convection pattern and magnetic field structure

Mid depth CZ

In Stable zone

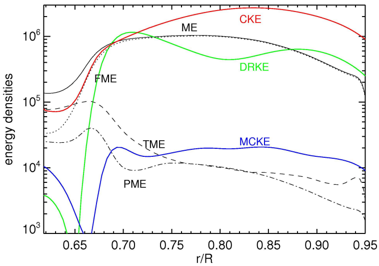


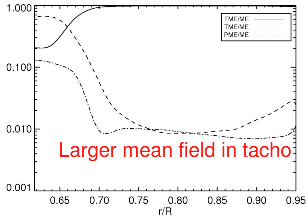
Vr

Bphi

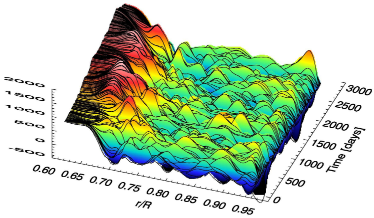
The B field is much more organized in tachocline (possessing an antisymmetric profile)

Energy Distribution vs normalized Radius





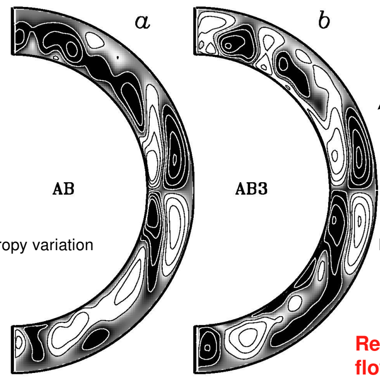
Larger mean field in tacho



m=0 toroidal field vs time and r

Predicting Meridional Circulation Deeper Down:

MC associated with case with conical Solar like profile



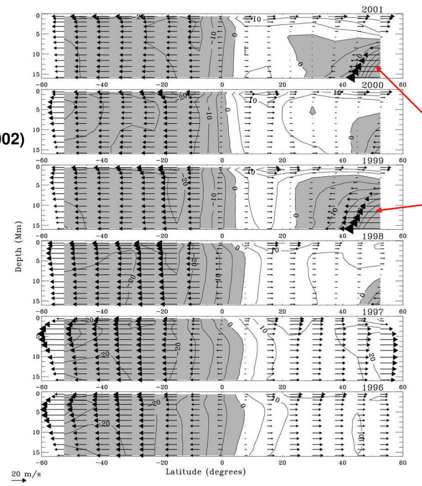
No imposed entropy variation

Imposed entropy variation

Retains multicellular flow pattern

Solar Meridional Circulation (MDI Data)

(Haber et al. 2002)



Appearance of a deep counter cell in the northern hemisphere

Pb: Babcock-Leigthon Type dynamos assume 1 cell!

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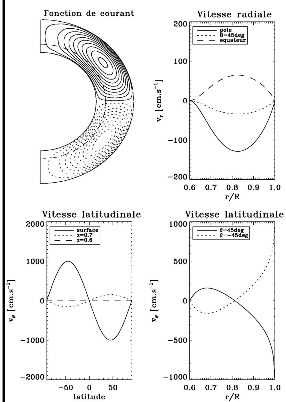
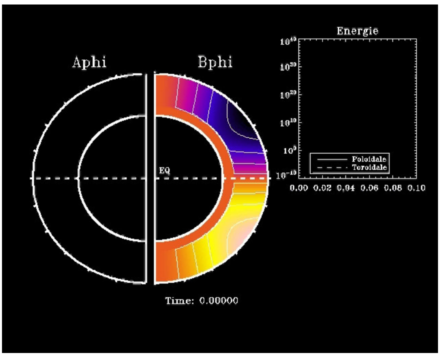
Testing Ideas: Influence of MC flow on Solar Cycle

2D Mean Field models: Babcock-Leighton

1 single cell per hemisphere





Jouve & Brun, 2005 submitted

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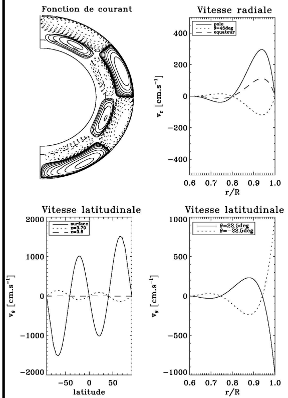
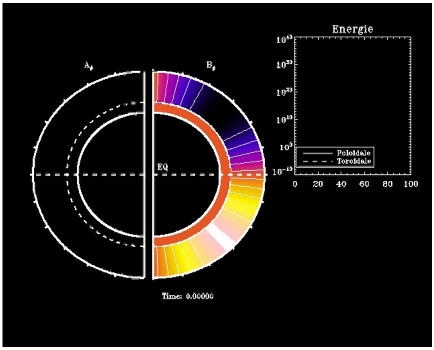
2D Mean Field models: Babcock-Leighton

2 cells in latitude, 2 in radius per hemisphere





Slow down cycle period:

$T=\exp(22.84)v_0^{-0.35}\eta_t^{-0.68}s_0^{0.017}$

For parameter values Identical to 1 cell case, find T=37 yr instead of 22

Jouve & Brun, 2005 submitted

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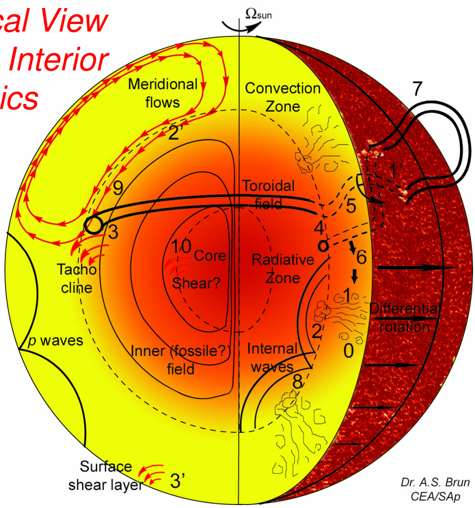
A Theoretical View of the Sun's Interior Dynamics



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Some Pending Issues

1. High Pm numbers of the simulation of turbulent dynamos (need specific LES-SGS closure, for exemple resolve fully B but « model » V for scales smaller than magnetic diffusivity scale, see Ponty et al. 2004)

2. What type of global dynamo in the Sun: Babcock-Leighton, $\alpha-\Omega$ or a mix of both types? Role of Meridional Circulation flows?

3. Need to further improve solar differential models and explain the solar rotation profile down to the nuclear core

4. What processes stop the tachocline to becoming thicker (Maxwell stresses, g-waves, anisotropic turbulence….?)

5. Interactions between « fossil » inner field and dynamo generated one?

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