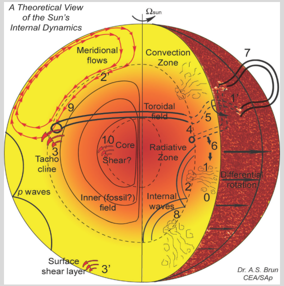
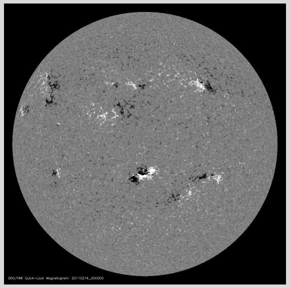
PHYS 7810 Special Topics in Physics: Physics of the Solar Atmosphere



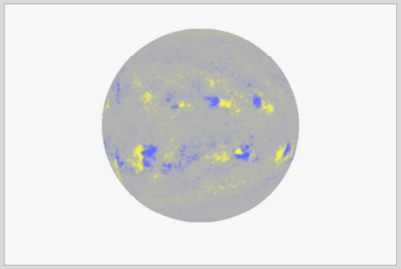


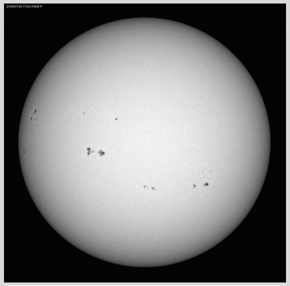
Matthias Rempel

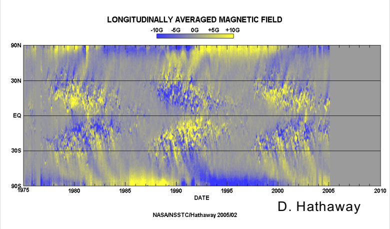
Lecture 5 Tues Jan 29 2019

https://www.nso.edu/students/collage/collage-2019/

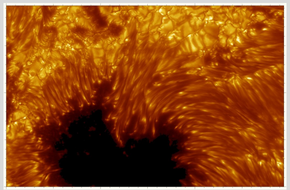
Solar magnetic field







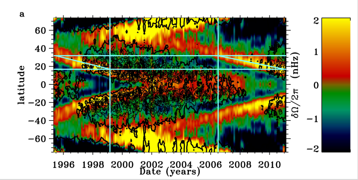
D. Hathaway

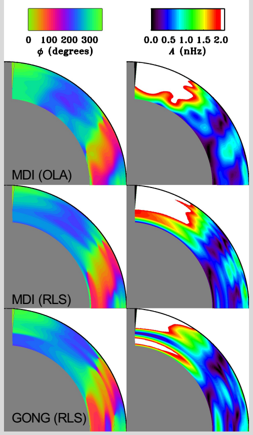


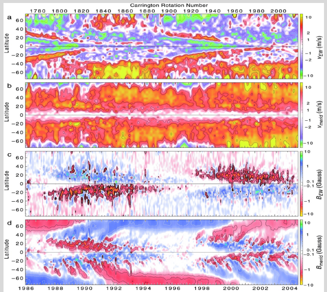
SST, La Palma

Large scale flow variations

Global Helioseismology (R. Howe)





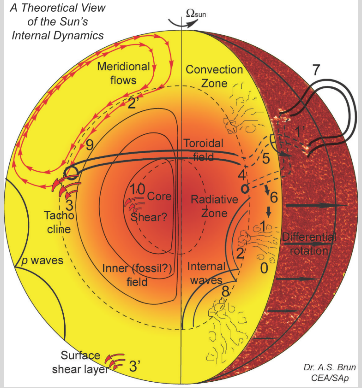


Surface Doppler (R. Ulrich)

Solar dynamo models – what is the goal?

- What is a solar dynamo model supposed to do?
  1) Show a "solar-like" activity pattern in terms of:
     - Cyclic behavior with equator-ward propagation of activity
     - Surface flux evolution consistent with observations
     - Large scale flow variations consistent with observations
  2) Show a "solar-like" amplitude variation from cycle to cycle
  3) Allow prediction of future activity
- Most models struggle already with point 1)
  - Focus this lecture on 1)
  - 2) and 3) can provide additional constraints on dynamo models

The basic dynamo ingredients



- Large-scale flows
  - Differential rotation
  - Meridional flow
  - Mean and (cyclic) variation
- Turbulent induction
  - Transport
    - Advective
    - Diffusive
  - α-Effects
    - Key terms that enable dynamo action
- Flux emergence
  - Links dynamo to photospheric field observations
  - Might play role in dynamo process itself
    - Babcock-Leighton mechanism

Numerical modeling approaches

- Meanfield models
  - Solve equations for mean flows, mean magnetic field only
  - Inexpensive, but need good model for correlations of small scale quantities (e.g. turbulent angular momentum transport), see extensive work by Rüdiger & Kitchatinov)
  - Can address the full problem, but not from first principles (models have many degrees of freedom and tunable parameters)
- 3D numerical simulations
  - Solve the full set of equations (including small and large scale flows, magnetic field) from first principles
  - Very expensive:
    - Low resolution runs for long periods >10 years
    - High resolution for short periods
  - Good understanding of differential rotation, ingredients of solar dynamo, no complete model yet
- Advances in computing infrastructure shift balance toward 3D simulations, but we need both!

Mean field models

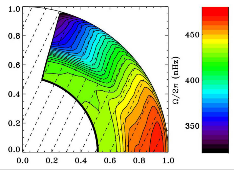
- Mean field models consider only average quantities
  - Sunspots are a key feature of the solar cycle, but they are averaged away
- Mean field models make strong assumptions that are not well justified from first principles
- Too many degrees of freedom require "educated guesses"

$$\overline{(v' \times B')}_i = a_{ik}\overline{B}_k + b_{ijk}\frac{\partial \overline{B}_j}{\partial x_k}$$

  - Contains 36!!! (mostly unknown) functions of r and ϑ, in most models only 2 are considered and even that allows for a lot of freedom
  - Computing mean field coefficients from 3D simulations (Schrinner et al. 2007, Ghizaru etal. 2011) shows that in general almost all of them are important!
- Mean field models allow us to study certain scenarios or they allow to analyze a complicated 3D simulation, but one has to be very lucky to find the "correct" model for the solar cycle without additional knowledge
- Non-linear feedback difficult to implement

Solar dynamo models

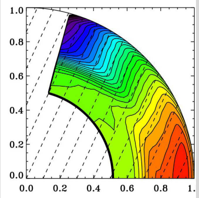
- Mean field models
  - Convection zone dynamos
  - Tachocline/interface dynamos
  - Near surface shear layer dynamos
  - Flux transport dynamos

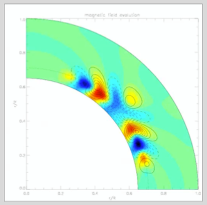


- Main uncertainties
  - Location of dynamo
  - Poloidal field regeneration (B_r, B_ϑ from B_φ: α-effect)
  - Turbulent transport (magnetic pumping, turbulent diffusion vs. magnetic buoyancy)
  - Role of meridional flow (propagation of activity belt)

Mean field dynamos

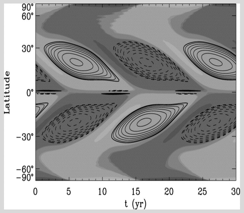
- Thin layer dynamos
  - Overshoot/tachocline dynamos
    - Radial shear, αΩ-type dynamos, latitudinal propagating dynamo wave
    - Negative α in northern hemisphere for equatorward propagation
  - Surface shear layer?
  - Main problem:
    - Typically very short latitudinal wave length (several overlapping cycles)
- Distributed dynamos
  - Interface dynamos
    - Ω-effect in tachocline, α-effect in CZ, introduced to avoid problems with strong α-quenching
    - Solutions very sensitive to details





Mean field dynamos

- Distributed dynamos
  - Flux transport dynamo
    - Advective transport of field by meridional flow
    - Propagation of AR belt advection effect
    - Cycle length linked to overturning time scale of meridional flow
  - Central assumption:
    - Proper meridional flow profile (mostly single flow cell poleward at top, equatorward near bottom of CZ)
    - Weak turbulent transport processes
    - Babcock-Leighton α-effect
  - Overall:
    - Most successful in reproducing solar like behavior

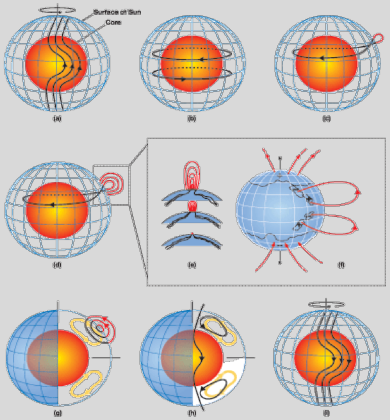


Dikpati et al. 2004

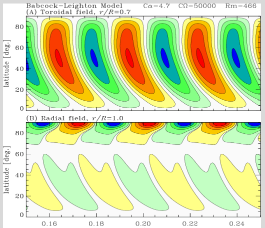
Schematic of a Babcock-Leighton flux transport model

(Durney,Choudhuri,Schüssler,Dikpati,Nandi,Charbonneau,Gilman,Rempel,Hotta)

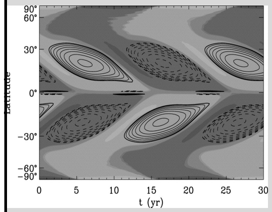
- Differential rotation
  - Toroidal field production
  - Stored at base of CZ
  - Rising flux tubes
- Babcock-Leighton α effect
  - Tilt angle of AR
  - Leading spots have higher probability to reconnect across equator
- Transport of magnetic field by meridional flow



Solution properties flux transport dynamos



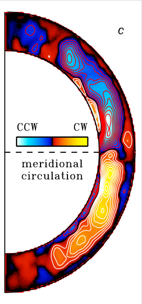
Dikpati & Charbonneau (1999)



Dikpati et al. (2004)

- Good agreement with basic cycle properties
  - Equatorward propagation
  - Weak cycle overlap
  - Correct phase relation between poloidal and toroidal field
- Less good agreement
  - Poleward extension of butterfly diagram?
  - Polar surface field typically too strong
  - Symmetry of solution (quadrupole preferred)
- More complicated ingredients can improve agreement
  - Strong variation of magnetic diffusivity in CZ
  - Additional α-effect at base of CZ
- Expense: Strong sensitivity to many not well known ingredients

Meridional flow structure, assumptions flux transport dynamo

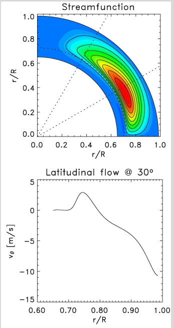


3D simulation
Miesch et al. (2008)

- Observations
  - Poleward near surface (surface Doppler and local helioseismology agree well)
  - Recent results indicate shallow return flow (Hathaway 2011)?
- Theory
  - Mean field models: single flow cell, related to inward transport of angular momentum
  - 3D: low res runs multi cellular, recent high res single cell, results not yet converged
- Advection dominated regime difficult to realize:

$$\eta_{turb} \propto H_p V_{rms}$$

$$V_{merid} \propto V_{rms}^2 / V_{rot}$$



Mean field model
Rempel (2005)

3D simulations

- Solve the full set of equations (including small and large scale flows, magnetic field) from first principles
  - No shortcuts, have to solve for the full problem including differential rotation and meridional flow
  - Non-linear effects automatically included
- Intrinsic limitations
  - Boundary conditions (radial direction)
    - Tachocline at base of CZ
    - Top boundary typically 20 Mm beneath photosphere
  - Cannot capture solar Re and Rm, how to treat small scales
    - DNS: resolve dissipation range with artificially increased diffusivities
    - (I)LES: do only the minimum required to maintain numerical stability
- Very expensive
  - Low resolution runs for long periods >10 years
  - High resolution for short periods
- Good understanding of differential rotation, ingredients of solar dynamo, no complete model yet

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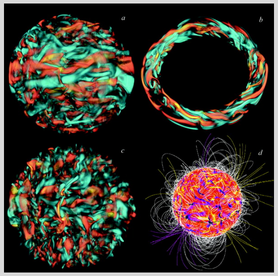
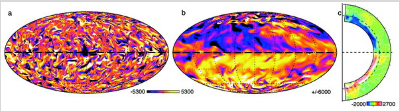
3D dynamo simulations

- 1981 Gilman & Miller
  - First 3D convective dynamos in a spherical shell (Boussinesq)
- 1983 Gilman
  - Dynamo simulations with reduced diffusivities
    - large scale field and periodic field reversal
    - poleward propagation
- 1985+ Glatzmaier …
  - Mostly 3D geodynamo models
- 2004 Brun, Miesch, Toomre
  - Turbulent dynamo (anelastic)
    - 800 G peak toroidal field
    - Mean field 2% of energy
    - No cyclic behavior

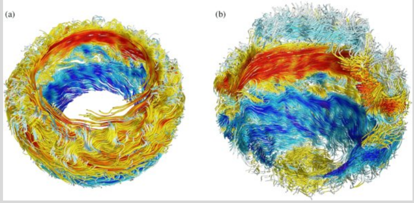


3D dynamo simulations

- 2006 Browning et al.
  - Addition of tachocline
  - Organized ~5 kG field in stably stratified region

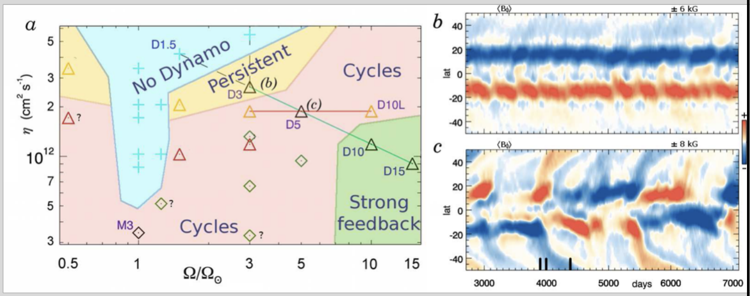


- 2008+ Brown et al.
  - Faster rotating stars
  - Strong field (~10 kG) maintained within CZ
  - Cyclic behavior for certain parameter choices (faster rotation)



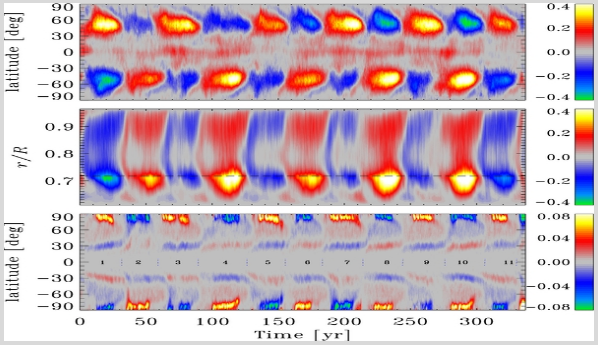
Cyclic dynamo regimes

- 2011 Brown et al.
  - Cyclic behavior typically found for sufficiently high Rm
    - Small diffusivity
    - Fast rotation

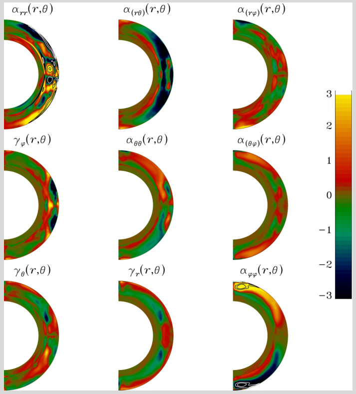


3D dynamo simulations

- 2010 Ghizaru et al., 2011 Racine et al.
  - Cyclic αΩ-type dynamo 60 yr period
  - Magnetic field generated near base of CZ



Characterization of large-scale dynamo (Ghizaru etal. 2011)

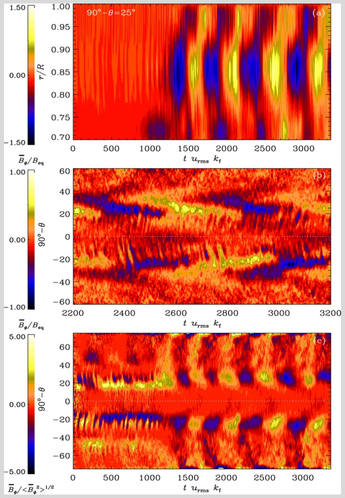


$$(\overline{v' \times B'})_i = (\alpha_{ik} + \varepsilon_{ijk}\gamma_j)\overline{B}_k$$

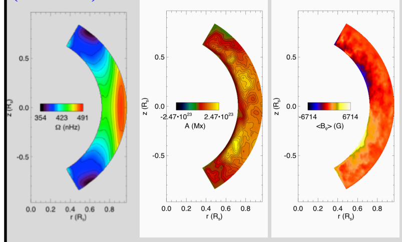
- All components have comparable amplitude
- Strongest effect present in diagonal elements, but substantial deviation from isotropy
  - $\alpha_{\vartheta\vartheta}$ and $\alpha_{\varphi\varphi}$ show pattern that reflects expectation from helicity profiles, but not α_{rr}
- Turbulent pumping
  - Down- and equatorward in bulk on convection zone
  - Poleward near surface in high latitudes
  - Mimics /competes with meridional flow

3D dynamo simulations

- Kapyla et al. (2012)
  - 33 year period
  - Field generated in bulk of CZ
  - Equatorward propagation below 40 deg latitude
  - Cycle length non-linear effect
    - Much shorter cycles during kinematic growth phase
    - “Phase transition” due to non-linear feedback



Simulations of convective dynamo in the solar convective envelope with the FSAM code (Fan 2013)

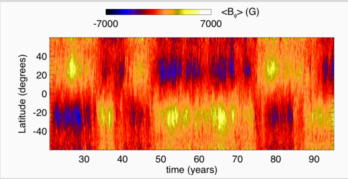


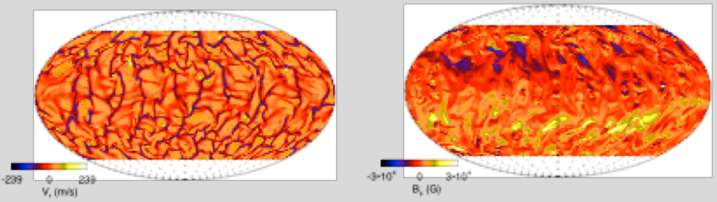
domain $r \in (0.722 R_s, 0.97 R_s)$, $\theta \in (\pi/2 - \pi/3, \pi/2 + \pi/3)$, $\phi \in (0, 2\pi)$

grid: $96 \times 512 \times 768$

$\kappa = 3 \times 10^{13}\, cm^2 s^{-1}$, $\nu = 1.5 \times 10^{12}\, cm^2 s^{-1}$, $\eta = 1.5 \times 10^{12}\, cm^2 s^{-1}$,

at top and all decrease with depth as $1/\sqrt{\rho}$

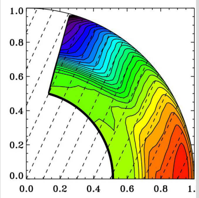


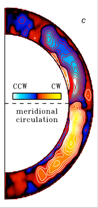


3D dynamo simulations

- Recent developments:
  - Several independent groups find cyclic dynamos with periods in the 10-60 year range
  - Some models with equatorward propagation of activity
  - No simple explanation for cycle length and magnetic field patterns
    - Cycle length non-linear effect (longer cycles in saturated phase)
    - Not obvious if different models get similar solutions for the same reason
- Contrast to meanfield models:
  - In general no single dominant turbulent induction term (like a scalar α-effect) that could capture the behavior
  - Non-linear feedback more than just saturation effect (i.e. long cycle length only found in non-linear regime)

What are the main uncertainties?





Miesch et al. 2008

- Large scale flows:
  - Differential rotation well known
    - Role of latitudinal vs. radial shear not clear

      Ω − effect $B_p \cdot \nabla\Omega$

      $\frac{\partial\Omega}{\partial r} > \frac{1}{r}\frac{\partial\Omega}{\partial\vartheta}$, but typically $B_r < B_\vartheta$
    - Role of tachocline (essential or does it just shape activity)
      - Fully convective stars show strong activity!
    - Variation of Ω (torsional oscillations) very small
      - Weak magnetic feedback or DR strongly driven?
      - What does this tell us about saturation?
  - Meridional flow
    - Poleward at surface
    - Flow structure in CZ?
    - Shallow return flow (Hathaway 2011)?

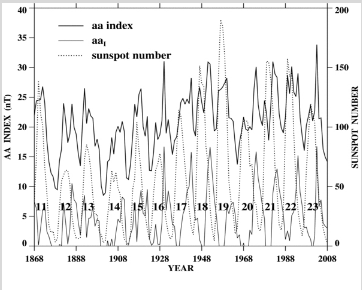
What are the main uncertainties?

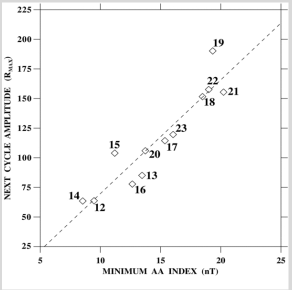
- Turbulent induction/transport
  - In most 3D simulations turbulence is more complicated than a combination of diffusion, advection and α-effects
  - Flux transport dynamos assume weak (< 10% of MLT estimates) turbulent transport processes - is that reasonable?
    - η has to be small, but not ν and κ (need to transport energy and maintain DR)?
    - no clear indication from numerical experiments for asymmetric magnetic quenching of η, ν and κ
  - More general problem
    - Diffusivities of the order $\eta_{turb} \propto H_p V_{rms}$ give too short cycles
    - Are longer cycles an intrinsically non-linear effect?
  - How is the poloidal magnetic field maintained?
    - kinematic (turbulent) α-effect?
    - magnetic saturation, role of magnetic helicity?
    - driven by magnetic instabilities?

What are the main uncertainties?

- Flux emergence process
  - By-product of dynamo or essential part of dynamo process?
    - 10^{24} Mx is a lot of flux: 10 kG x 100x100 Mm^2
  - Poloidal field in photosphere consequence of AR tilt angle
    - Babcock-Leighton α-effect
    - Is that enough to drive the dynamo?
      - Polar flux ~ 10^{22} Mx about 1% of flux emerging in AR
      - How to get back to 100%
      - DR can do ~100!
- What determines field amplitude
  - Feedback on DR, meridional flow?
  - Quenching of turbulent induction (magnetic helicity) ?

What do the observations tell?





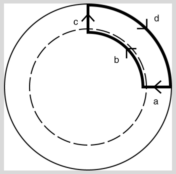
Wang & Sheeley 2009

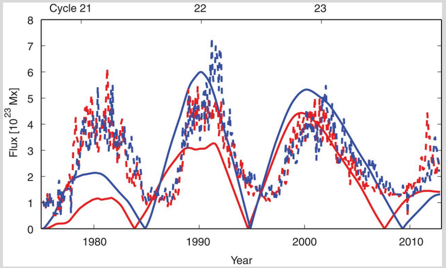
- Geomagnetic activity related to solar high speed streams (solar minimum) and CMEs (solar max)
- High speed streams during minimum related to flux of polar caps -> poloidal field of sun during minimum
- Shows strong correlation with upcoming cycle amplitude

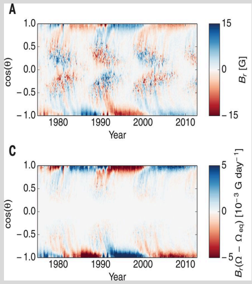
Surface flux evolution and net toroidal flux

$$\frac{d\Phi^N_{tor}}{dt} = \frac{d}{dt}\left(\int_\Sigma B_\phi dS\right) = \int_{\delta\Sigma}\left(\mathbf{U}\times\mathbf{B} + \langle\mathbf{u}\times\mathbf{b}\rangle - \eta\nabla\times\mathbf{B}\right)\cdot d\mathbf{l}$$

$$\frac{d\Phi^N_{tor}}{dt} = \int_0^1 (\Omega - \Omega_{eq}) B_r R_\odot^2 d(\cos\theta) - \frac{\Phi^N_{tor}}{\tau}$$



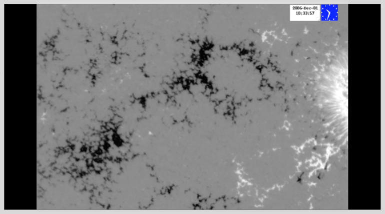




Robert Cameron, and Manfred Schüssler Science 2015;347:1333-1335

Flux emergence and sunspot formation

- General accepted view
  - Magnetic flux rising toward surface from deep convection zone
  - Observations show at first strong horizontal expansion of emerging flux
- Key question
  - Transport of flux through convection zone and re-amplification in photosphere:
    - Density contrast of 10^6
      - $B \sim \rho^\varepsilon$ ε = 1/2 …. 2/3
      - 100 kG -> 100 G
      - 100 G -> 3kG ???
    - Vigorous convection



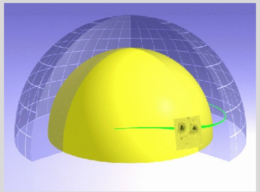
Flux emergence event observed with Hinode SOT

Modeling of flux emergence

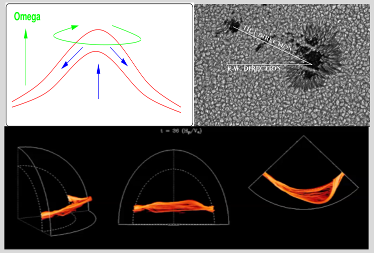
- Lower convection zone (up to ~ 20 Mm depth beneath photosphere)
  - Strongly subsonic velocities
  - Ideal gas equation of state sufficient
  - Size of flux tubes smaller than Hp and typical scale of convection
    - Flux tubes travel several times their diameter
    - Interaction with ambient flows (including flows created by rising flux) key to dynamics
    - Density contrast of 100 (out of 10^6)
  - Modeling approaches
    - Thin flux tube approximation
    - 3D anelastic MHD models
    - Both with and without background convection

Flux emergence in lower convection zone

(Caligari, Fan, Fisher, Moreno-Insertis, Schüssler …)



Thin flux tube simulation: Caligari et al. (1995)

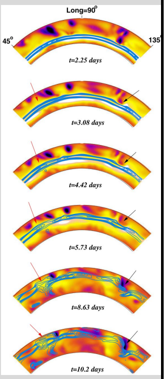


3D simulation: Fan (2008)

- Consistent results from thin tube and 3D simulations
- Coriolis force causes tilt of the top part of tube
- Explains asymmetry between leading/following spot
- Works best with ~ 100 kG flux tubes
  - Consistent with stability considerations in overshoot region
  - Too strong for dynamo models
- Twist required for 2D/3D simulations
  - Prevents fragmentation
  - Induces additional tilt (opposing that from Coriolis force)
  - Trade off between stability and tilt

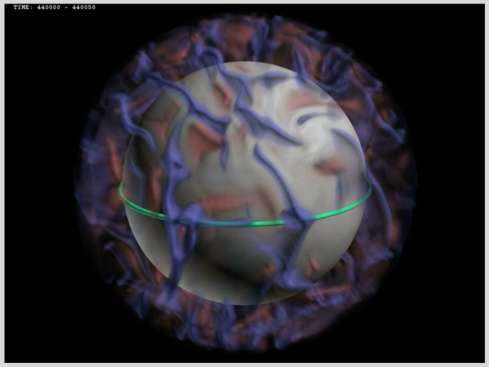
Interaction with convection

- 3D anelastic MHD (Jouve & Brun 2009)
  - Self consistent interaction with convection, differentia rotation and meridional flow (Global convection zone simulation)
  - Convective motions additional source of tilt, substantially shape tube during rise
  - Challenge: Focus on global picture limits resolution on the scale of flux tube, requires tubes with $>>10^{22}$ Mx flux
- Thin flux-tubes rising in convective background
  - Take velocity from global CZ simulation
  - Treat flux tube as thin tube
  - Weber, Fan & Miesch 2011



Jouve & Brun (2009)

Interaction with convection



Weber, Fan & Miesch (2011)

- Thin flux tube rising in convective envelope (taken from global 3D simulation)
- Flux tube evolution mostly dominated by convective time scales
- Less dependence on initial field strength
  - Best results for 40-50 kG (100-150 kG without convection)

Flux emergence in upper most 20 Mm

- Upper convection zone
  - Subsonic/supersonic transition velocities
  - Partial ionization, 3D radiative transfer important
  - Size of flux tubes larger than Hp and typical scale of convection
    - Flux ‘tubes’ travel about their diameter
    - Density contrast of 10^4 (out of 10^6)
    - Dynamics dominated by strong expansion
    - Most weakening of field strength near surface
  - Modeling approaches
    - Fully compressible MHD (with RT and realistic EOS)
- Currently treated independent from deep convection zone (computational constraints)

Flux emergence, sunspot formation

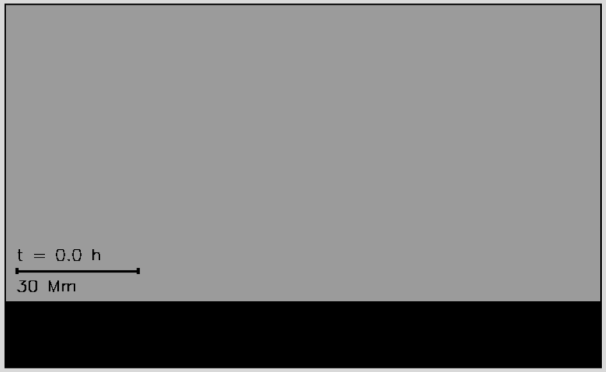
Magnetogram

(tau=1)

Domain size:

150x75x16 Mm

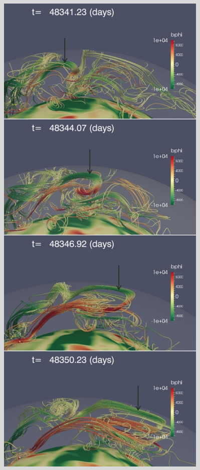
|B|
(vertical slice)



Rempel & Cheung 2014

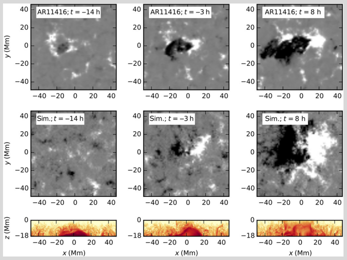
Flux emergence and active region formation a changing paradigm

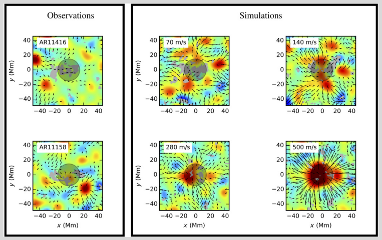
- Early work based on rising thin flux tube
  - Caligari, Schuessler, Moreno-Insertis, Ferriz-Mas, Fan, Fisher …. ~1993-1996
  - Strong ~100 kG flux tubes rise from base of CZ
    - Buoyancy instabilities in Overshoot region
    - Flux emergence in low latitudes
    - Tilt angles
  - Retrograde flows due to angular momentum conservation
  - Asymmetric stretching of rising loop leads to stronger leading legs
- Thin flux tube models including ambient convection
  - Weber et al. (2011 – 2015)
  - Advective transport by ambient convection significant
  - Less sensitive to initial field strength
  - Tilt a combination of Coriolis forces and ambient helical flows
- 3D global dynamo models
  - Nelson et al. 2014, Fan & Fang 2014
  - Flux bundles originate within CZ ~10 kG, non-axisymmetric zonal shear significant
  - Convective/buoyant transport towards surface in giant cells
  - Prograde flows in emerging flux regions

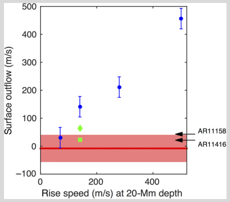


Fan & Fang (2014)

Helioseismic constraints on emergence speeds in upper CZ



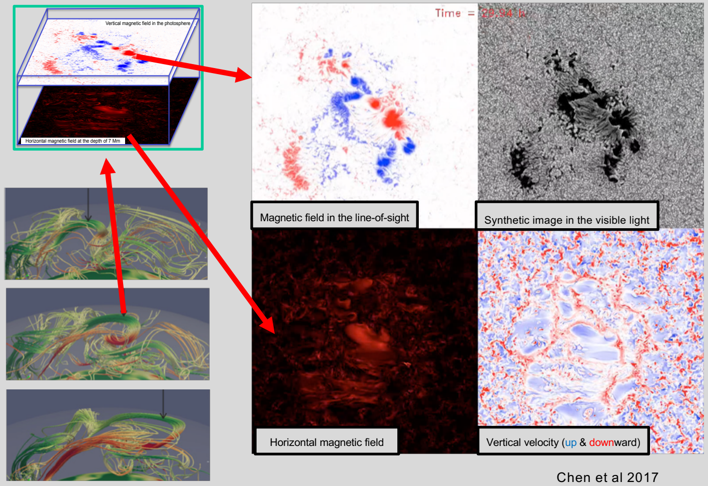




From Birch et al . 2015

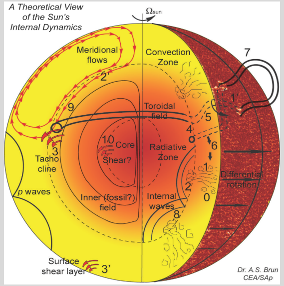
- Observed AR (sample of ~100) show little to no evidence of diverging flows in excess of those found in ambient convection
- Flux emergence models are only consitent with these constraints if the emergence speed is comparable or even smaller than typical convective upflows
- Flux emergence in the upper most 20 Mm of the CZ is mostly a passive process.

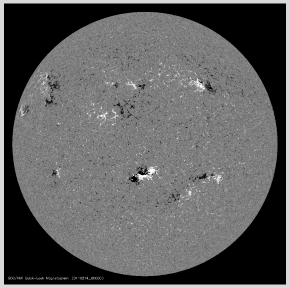
Coupled flux emergence simulations: 3D global convective dynamo into photosphere and beyond



Chen et al 2017

PHYS 7810 Special Topics in Physics: Physics of the Solar Atmosphere





Matthias Rempel

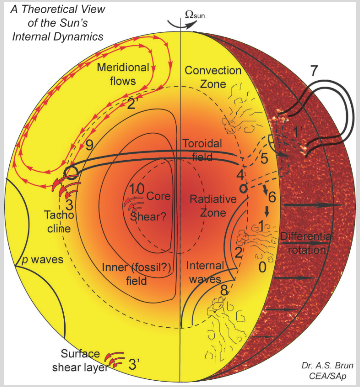
Lecture 6 Thurs Jan 31 2019

https://www.nso.edu/students/collage/collage-2019/

Outline

- Energy transport in solar convection zone, photosphere and above
- Origin and structure of magnetic field in the solar photosphere
- Magnetic modulation of solar energy output

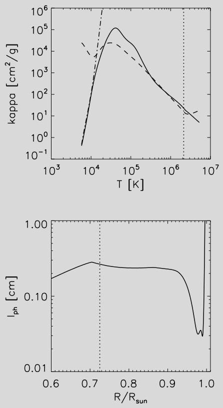
Structure of the solar interior



- Radiative interior
  - 0 … 0.72 R
- Convection zone
  - 0.72 … 1 R
- Solar magnetic activity
  - Dynamo process in convection zone

S. Brun

Basic structure of convection zone



Solar model: Kiefer & Stix

- ➢ Radiative energy flux (diffusion approximation)

$$F_{rad} = \frac{1}{3} c l_{ph} \frac{d}{dr} a T^4$$

- ➢ Photon mean free path (kappa is here the Rosseland mean opacity)

$$l_{ph} = \frac{1}{\kappa \rho}$$

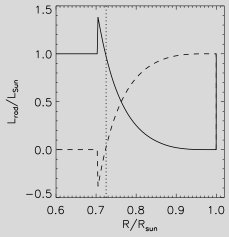
- ➢ Opacity sources
  - – T>3x10⁴ K: free-free, bound-free transitions:

$$\kappa \propto \rho T^{-3.5}$$

  - – T<10⁴ K: negative H ion (0.75 eV)

$$\kappa \propto \rho^{0.5} T^9$$

Basic structure of convection zone

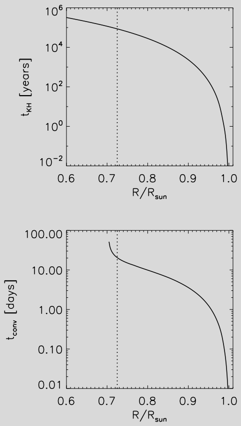


- ➢ Radiative energy flux (diffusion approximation)

$$F_{rad} = \frac{1}{3} c l_{ph} \frac{d}{dr} a T^4$$

- ➢ Drop of radiation energy density makes RT inefficient (l_{ph}~ const)
  - – Temperature gradient increases until convective instability sets in
- ➢ Convection zone in between 2 radiative boundary layers
  - – Bottom: L ~ 100 Mm
  - – Top: L ~ 100 km

Time scales of convection zone



- ➢ Kelvin-Helmholtz time scale:

$$t_{KH}(r) = \frac{\int_r^{R_{Sun}} 4\pi r^2 E_{\mathrm{int}} dr}{L_{Sun}}$$

- ➢ Convective overturning time scale

$$t_{Conv}(r) = \frac{H_p(r)}{v_{Conv}(r)}$$

- ➢ Convection zone is a well mixed reservoir with a large heat capacity
  - – Thermal properties of CZ respond very slowly to a disturbance of the energy flux

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Key properties of convection zone

- ➢ Convection driven by strong cooling at the top and gentle heating at the bottom
  - – Resolving the top boundary is the key for understanding convective dynamics
- ➢ Convection zone has a large heat capacity and is well mixed
  - – ΔL~ 0.1% over solar cycle years does not lead to a significant temperature response in the convection zone
  - – Changes of F_{conv} in the bulk of the CZ likely do not lead to significant observable irradiance changes (this question is not fully settled)

Modeling the solar photosphere

- Key ingredients:
  - MHD
  - Radiative transfer
    - 3D, i.e. angular dependence resolved
    - Frequency dependence of opacity (capture by a few opacity bins)
  - Equation of state with partial ionization
- Open bottom boundary condition
  - Cannot afford simulation the entire convection zone
  - Use open bottom boundary conditions:
    - Convective energy flux across boundary
    - Downflows exit the domain with their thermal properties
    - Upflows have a prescribed fixed entropy

Photospheric MHD

Fully compressible MHD

$$\begin{aligned}
\frac{\partial \varrho}{\partial t} &= -\nabla\cdot(\varrho\mathbf{v}) \\
\frac{\partial \varrho\mathbf{v}}{\partial t} &= -\nabla\cdot(\varrho\mathbf{v}\mathbf{v}) + \mathbf{j}\times\mathbf{B} - \nabla P + \varrho\mathbf{g} \\
\frac{\partial E_{\rm tot}}{\partial t} &= -\nabla\cdot\left[\mathbf{v}\left(E_{\rm tot} + P + \frac{B^2}{8\pi}\right) - \frac{1}{4\pi}\mathbf{B}(\mathbf{v}\cdot\mathbf{B})\right] + \varrho\mathbf{v}\cdot\mathbf{g} + Q_{\rm rad} \\
\frac{\partial \mathbf{B}}{\partial t} &= \nabla\times(\mathbf{v}\times\mathbf{B})
\end{aligned}$$

With

$$E_{\rm tot} = E_{\rm int} + \frac{1}{2}\varrho v^2 + \frac{B^2}{8\pi}$$

Energy flux

$$\mathbf{F} = \mathbf{v}(E_{\rm int} + P) + \mathbf{v}\frac{1}{2}\varrho v^2 + \frac{1}{4\pi}\mathbf{E}\times\mathbf{B}$$

Enthalpy Kinetic energy Poynting flux

Photospheric radiative transfer

Radiative transfer equation (I specific intensity, $\hat{\mathbf{n}}$ unit vector in ray direction)

$$\frac{dI_\nu}{ds}(\hat{\mathbf{n}}) = \kappa_\nu \varrho (S_\nu - I_\nu(\hat{\mathbf{n}}))$$

Source function $S_\nu = B_\nu(T)$ in local thermodynamic equilibrium (LTE)

Radiative energy flux

$$\mathbf{F}_\nu = \int_{4\pi} I_\nu(\hat{\mathbf{n}})\hat{\mathbf{n}}\,d\Omega$$

Average intensity

$$J_\nu = \frac{1}{4\pi}\int_{4\pi} I_\nu(\hat{\mathbf{n}})\,d\Omega$$

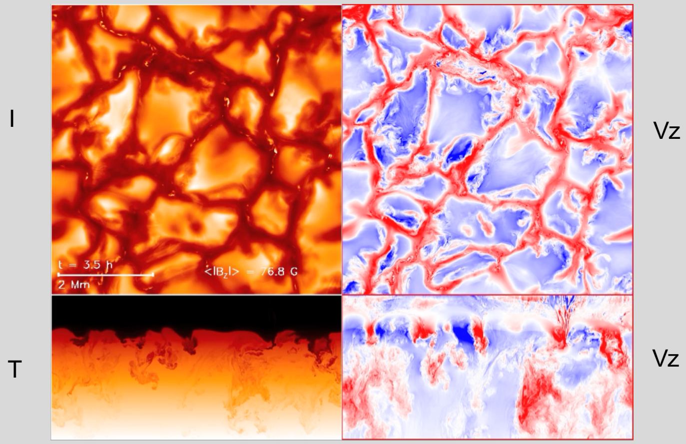
Radiative heating/cooling

$$Q_{\rm rad} = -\int_\nu (\nabla\cdot\mathbf{F}_\nu)\,d\nu = 4\pi\varrho\int_\nu \kappa_\nu (J_\nu - S_\nu)\,d\nu$$

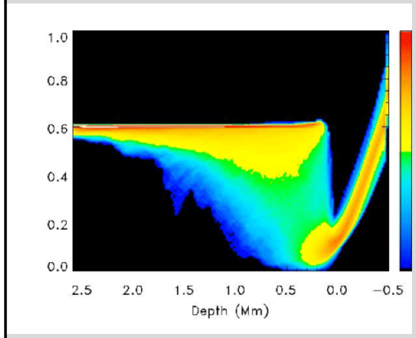
Numerical treatment

- Compute a discrete number of rays, typically 24 - 48
- Compute a discrete number of frequency bins, typically 1 - 12

Example granulation simulation



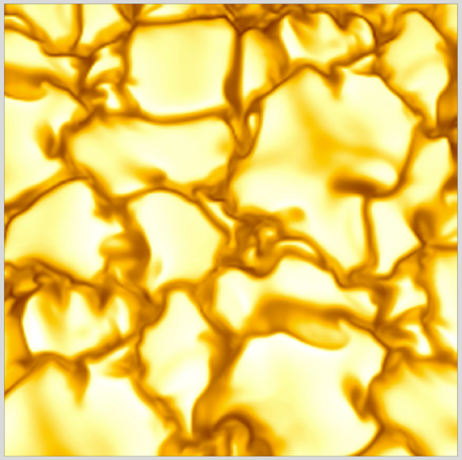
Thermal properties of up and downflows



Stein et al. 1997

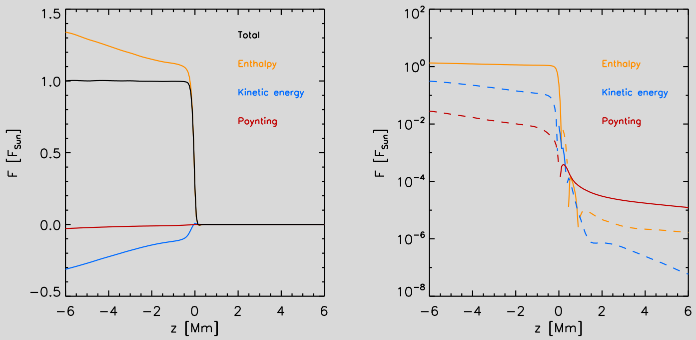
- ➢ Upflow entropy has little variation through the convection zone
  - – Adiabatic stratification
- ➢ Downflows start with a low entropy at the top due to radiative energy loss
- ➢ Downflow entropy increases with depth due to mass entraining from upflow regions
  - – Suparadiabatic stratification
- ➢ Average stratification superadiabatic

Corrugated photosphere



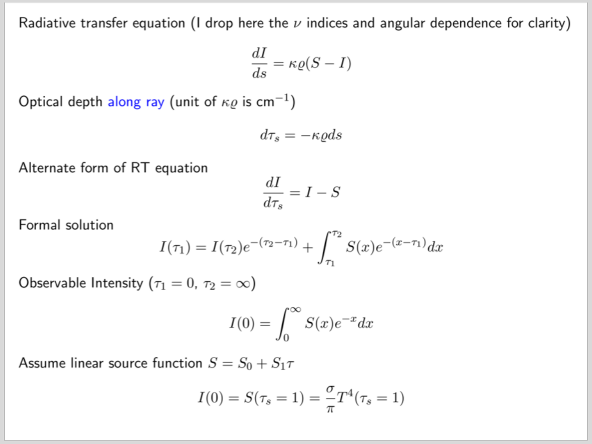
Mats Carlsson, Oslo

Energy fluxes



$$\mathbf{F} = \mathbf{v}(E_{\mathrm{int}} + P) + \mathbf{v}\frac{1}{2}\varrho v^2 + \frac{1}{4\pi}\mathbf{E} \times \mathbf{B}$$

Relation between intensity and photospheric properties



Radiative transfer equation (I drop here the ν indices and angular dependence for clarity)

$$\frac{dI}{ds} = \kappa\varrho(S - I)$$

Optical depth along ray (unit of $\kappa\varrho$ is cm^{-1})

$$d\tau_s = -\kappa\varrho ds$$

Alternate form of RT equation

$$\frac{dI}{d\tau_s} = I - S$$

Formal solution

$$I(\tau_1) = I(\tau_2)e^{-(\tau_2-\tau_1)} + \int_{\tau_1}^{\tau_2} S(x)e^{-(x-\tau_1)}dx$$

Observable Intensity ($\tau_1 = 0$, $\tau_2 = \infty$)

$$I(0) = \int_0^{\infty} S(x)e^{-x}dx$$

Assume linear source function $S = S_0 + S_1\tau$

$$I(0) = S(\tau_s = 1) = \frac{\sigma}{\pi}T^4(\tau_s = 1)$$

Magnetic modulation of photospheric emission

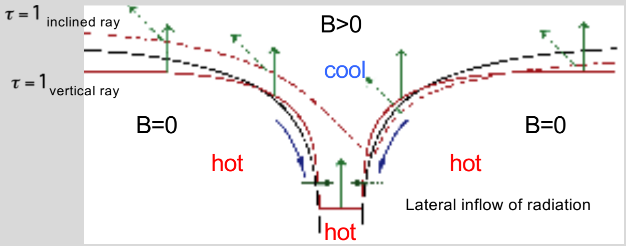
- Long lived, large-scale magnetic field concentrations
  - Suppression of convective energy transport
  - Energy radiated away in photosphere cannot be replenished
  - $S(\tau=1)=\frac{\sigma}{\pi}T^4(\tau=1)$ is reduced
  - Dark features, i.e. sunspot umbra
- Short lived, small-scale flux concentrations
  - Approximate pressure balance

$$p_i+\frac{B^2}{8\pi}=p_e \rightarrow p_i<p_e \rightarrow \rho_i<\rho_e$$

  - Flux concentration more transparent, i.e. radiation escapes from a deeper layer where T is larger
  - Lateral inflow of radiation keeps structure hot
  - $S(\tau=1)=\frac{\sigma}{\pi}T^4(\tau=1)$ is enhanced
  - Brightpoints, faculae
  - Typical required field strength (p_{phot} ~ 10^5 dyn/cm^2)

$$B\approx\sqrt{8\pi\, p_{phot}}\approx 1-1.5kG$$

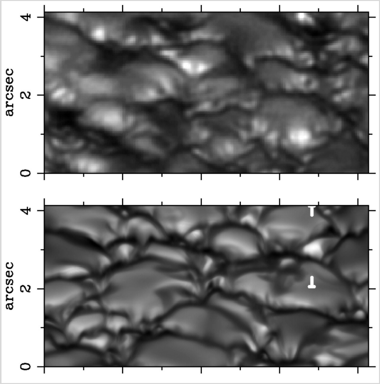
Angular dependence of brightening

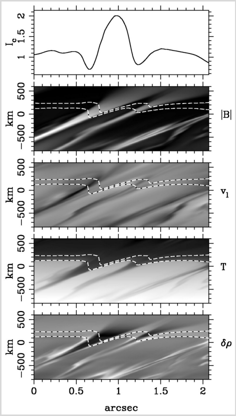


From Thaler & Spruit 2014

- Inclined rays more bright
  - Geometric projection effect
  - $\tau=1$ level deeper (i.e. hotter) near hot wall

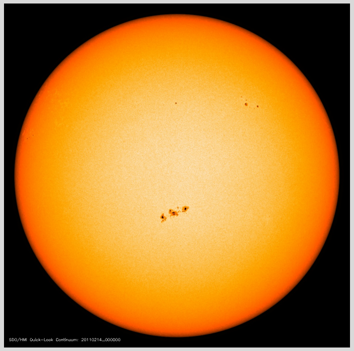
Simulated Faculae

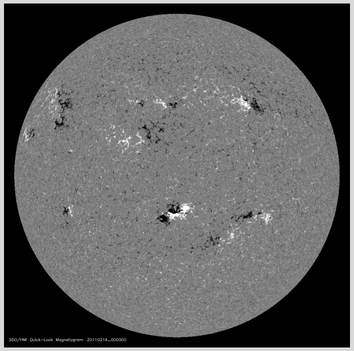




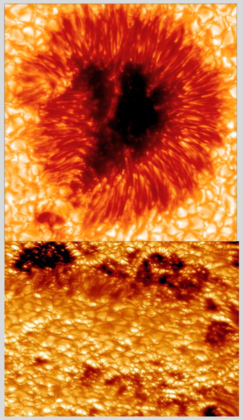
From Keller et al. 2004

Photospheric magnetic field
(solar surface dermatology)





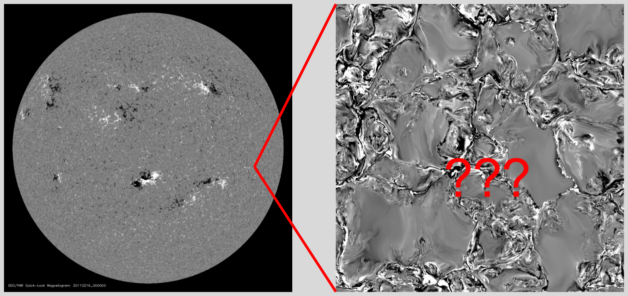
Phospheric magnetic field



Swedish solar telescope

- Active regions
  - Solar cycle variation
  - Origin: Large scale dynamo
  - Sunspots:
    - dark
  - Plage:
    - dark pores
    - bright faculae
- Quiet Sun
  - No convincing evidence for a cycle variation
  - Magnetic field independent from large scale dynamo
  - Grand minimum = quiet sun??

Quiet Sun magnetism

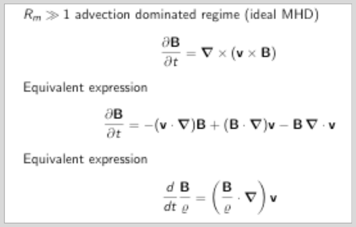


- Most of the solar surface is covered by “quiet Sun” at any time of the sunspot cycle
- Unsigned flux at τ=1 is a few times 10^{24} Mx, i.e. comparable to the flux emerging in form of active regions throughout the cycle
- Where does this field come from and what does it tell us about the solar dynamo(s)?

Quiet Sun – What are the open questions?

- How is the field distributed?
  - Spectral energy distribution
    - Preferred scale (i.e. “flux tubes” at 100 km) ?
  - Strength distribution
    - Fraction of kG field?
- Where does the field come from?
  - Remnant flux from active region decay
    - Only weak indication from observations
  - Small scale dynamo
    - Origin independent from solar cycle
    - Theoretical challenges

What is a small scale dynamo?



$R_m \gg 1$ advection dominated regime (ideal MHD)

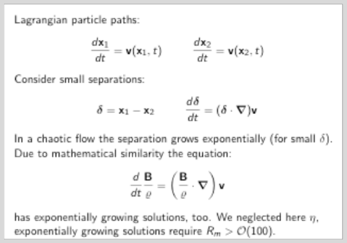
$$\frac{\partial \mathbf{B}}{\partial t} = \boldsymbol{\nabla} \times (\mathbf{v} \times \mathbf{B})$$

Equivalent expression

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

Equivalent expression

$$\frac{d}{dt}\frac{\mathbf{B}}{\varrho} = \left(\frac{\mathbf{B}}{\varrho} \cdot \boldsymbol{\nabla}\right)\mathbf{v}$$



Lagrangian particle paths:

$$\frac{d\mathbf{x}_1}{dt} = \mathbf{v}(\mathbf{x}_1, t) \qquad \frac{d\mathbf{x}_2}{dt} = \mathbf{v}(\mathbf{x}_2, t)$$

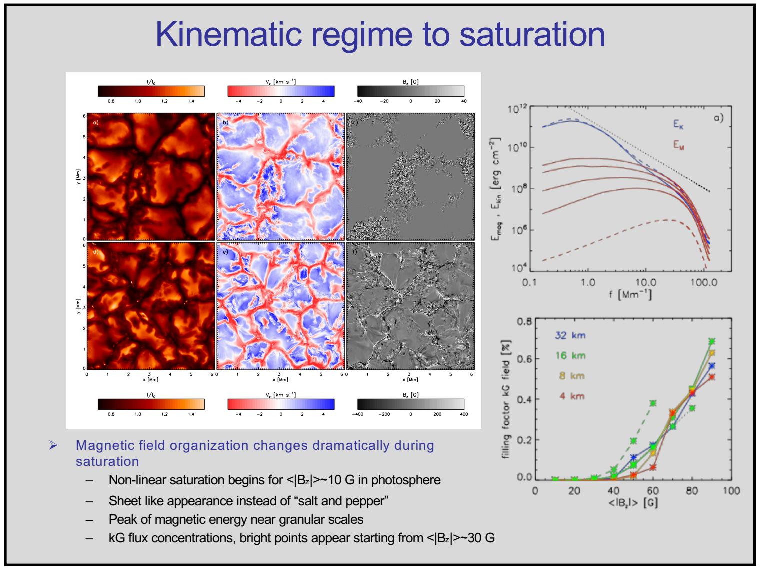
Consider small separations:

$$\delta = \mathbf{x}_1 - \mathbf{x}_2 \qquad \frac{d\delta}{dt} = (\delta \cdot \boldsymbol{\nabla})\mathbf{v}$$

In a chaotic flow the separation grows exponentially (for small δ). Due to mathematical similarity the equation:

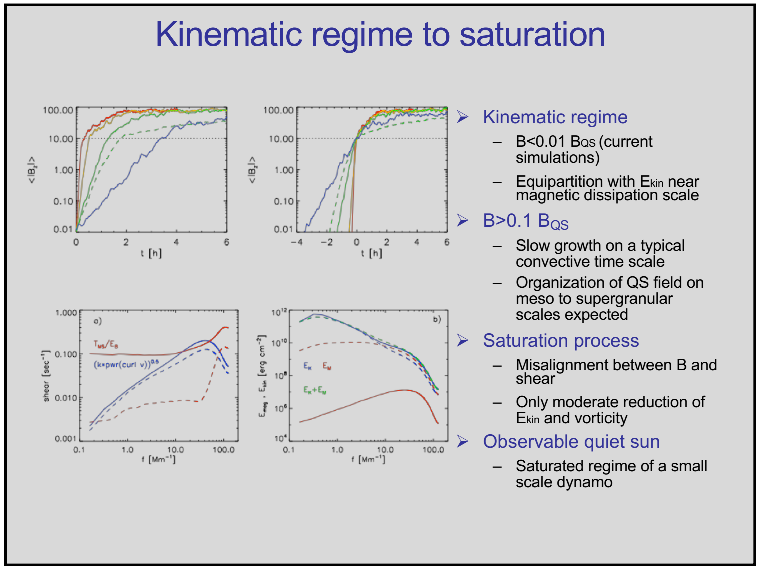
$$\frac{d}{dt}\frac{\mathbf{B}}{\varrho} = \left(\frac{\mathbf{B}}{\varrho} \cdot \boldsymbol{\nabla}\right)\mathbf{v}$$

has exponentially growing solutions, too. We neglected here η, exponentially growing solutions require $R_m > \mathcal{O}(100)$.



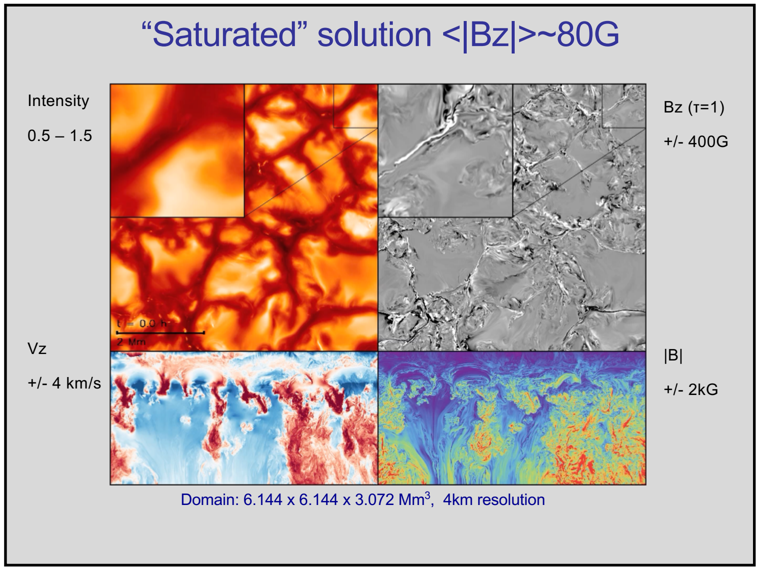
Kinematic regime to saturation

- Magnetic field organization changes dramatically during saturation
  - Non-linear saturation begins for <|B_z|>~10 G in photosphere
  - Sheet like appearance instead of “salt and pepper”
  - Peak of magnetic energy near granular scales
  - kG flux concentrations, bright points appear starting from <|B_z|>~30 G



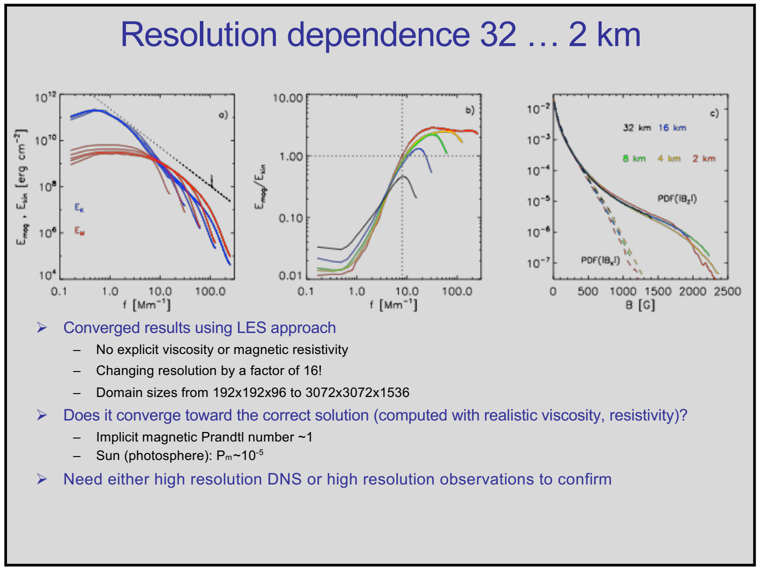
Kinematic regime to saturation

- Kinematic regime
  - B<0.01 B_{QS} (current simulations)
  - Equipartition with E_{kin} near magnetic dissipation scale
- B>0.1 B_{QS}
  - Slow growth on a typical convective time scale
  - Organization of QS field on meso to supergranular scales expected
- Saturation process
  - Misalignment between B and shear
  - Only moderate reduction of E_{kin} and vorticity
- Observable quiet sun
  - Saturated regime of a small scale dynamo



“Saturated” solution <|Bz|>~80G

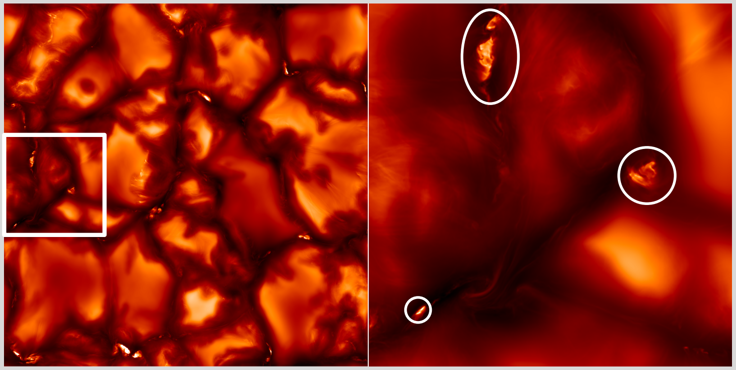
Domain: 6.144 x 6.144 x 3.072 Mm^3, 4km resolution



Resolution dependence 32 … 2 km

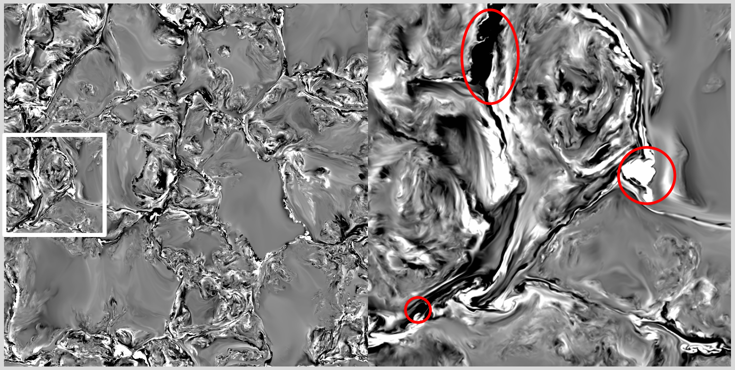
- Converged results using LES approach
  - No explicit viscosity or magnetic resistivity
  - Changing resolution by a factor of 16!
  - Domain sizes from 192x192x96 to 3072x3072x1536
- Does it converge toward the correct solution (computed with realistic viscosity, resistivity)?
  - Implicit magnetic Prandtl number ~1
  - Sun (photosphere): P_m~10^{-5}
- Need either high resolution DNS or high resolution observations to confirm

“Sun” at 2 km resolution



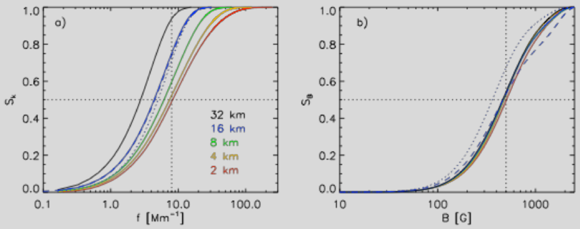
- Simulation domain: 6.144 x 6.144 x 3.072 Mm^3
- Grid size: 3072 x 3072 x 1536

“Sun” at 2 km resolution



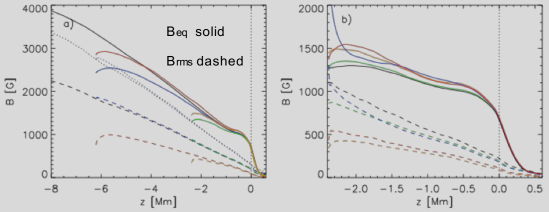
- Simulation domain: 6.144 x 6.144 x 3.072 Mm^3
- Grid size: 3072 x 3072 x 1536

Energy distribution in photosphere



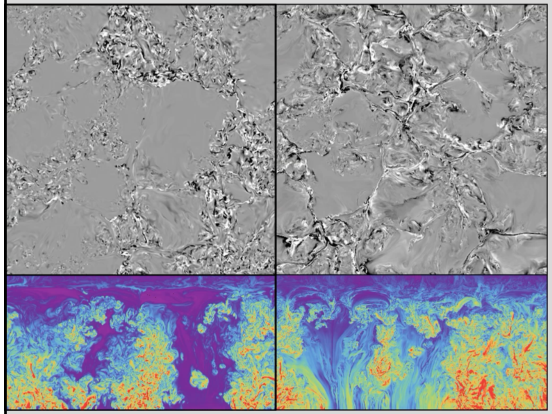
- ~50% of energy on scales smaller than 100 km
  - Need small (~8 km or smaller) grid spacing for properly resolving the spectral energy distribution
  - Hinode “sees” about 20% of the magnetic energy, DKIST could see more than 90%
- ~50% of energy from field weaker than 500 G
  - No resolution dependence, but domain size and overall field strength matters

Role of bottom boundary condition



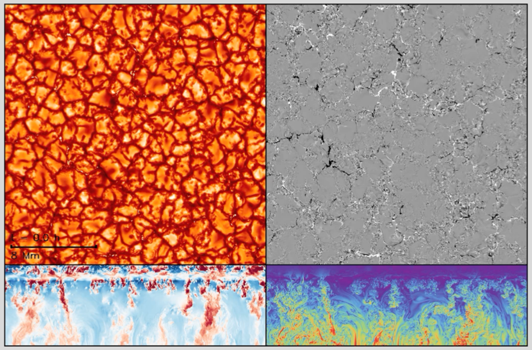
- Bottom boundary sets overall field strength reached in the photosphere in the range
  - $\langle|B_z|\rangle \sim 30 - 85$ G
- “Lower” bound (30 G):
  - B=0 in inflow regions, or vertical field boundary condition
  - Dynamo lives from **local** recirculation due to turbulent upflow/downflow mixing
  - Stronger field requires **global** recirculation (i.e. closed bottom boundary condition, open boundary with horizontal magnetic field in upflow regions, conditions of deep CZ influences photosphere)
- “Upper” bound (85 G):
  - B_{rms} increases at same rate as B_{eq}

Local vs. global recirculation



- Left:
  - B=0 in inflow regions
- Right
  - B symnmetric across boundary
  - Similar to closed boundary with full recirculation

Meso-granular scales



Intensity

0.5 – 1.5

Bz (τ=1)

+/- 400G

Vz

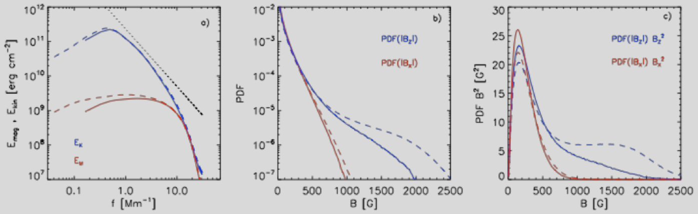
+/- 4 km/s

|B|

+/- 4kG

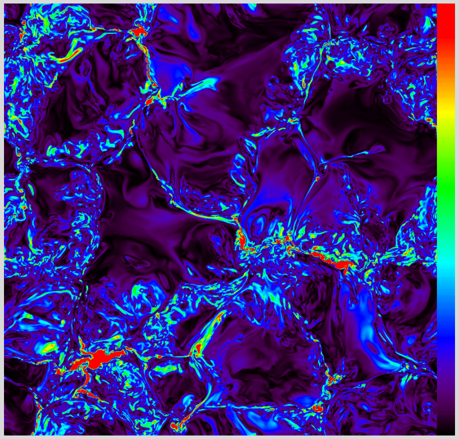
- Small-scale dynamo operating in a highly stratified domain
  - Dynamo operates over a wide range of scales at different depth, coupled through vertical transport
  - Can organize magnetic field on scales larger than granulation
  - Can lead to significant local flux imbalance

Meso-granular scales



- Increase of domain size leads to
  - Increase of magnetic power on large scale
  - Indication of a flat magnetic power spectrum on scales larger than granulation
  - Increase of kG field fraction, but no indication of a secondary peak in PDF (requires > 30 G flux imbalance)

Larger scale organization and “voids”

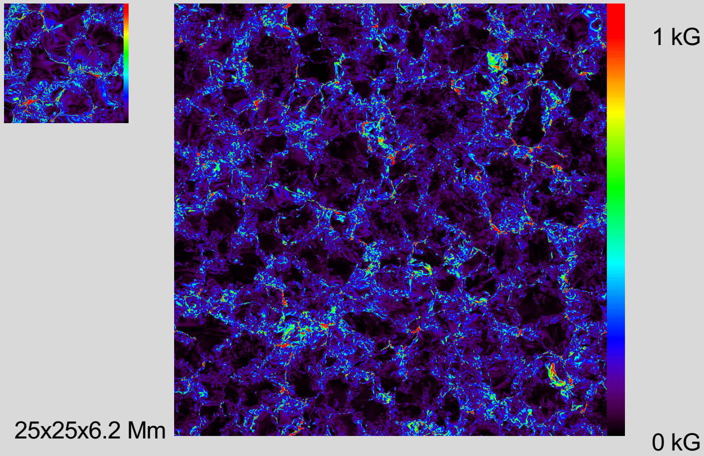


1 kG

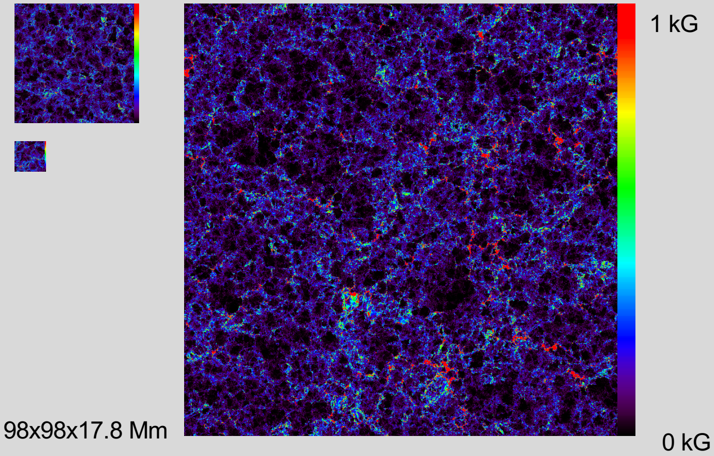
6x6x2.3 Mm

0 kG

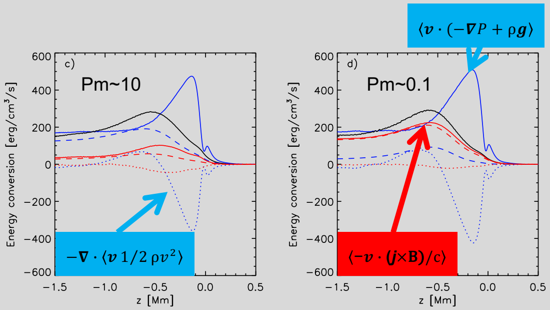
Larger scale organization and “voids”



Larger scale organization and “voids”



SSD energetics



- About 150 erg/cm^3/s “convective driving” available in upper CZ/photosphere to drive dynamo
- Energy transfer to magnetic energy strongly Pm dependent (Brandenburg 2011, 2014)
- Most efficient dynamos (in terms of energy conversion) found for low Pm regime
- Uppermost 1.5 Mm of convection zone: About >0.3 L_{Sun} converted to B