Theories and observations of surface dynamo

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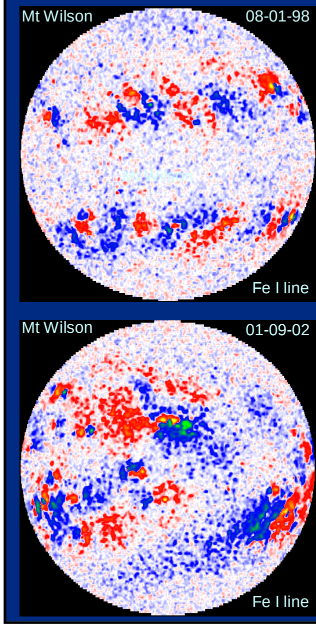
Plan

- Surface dynamo?
- Theory
- Observations
- Challenges

Large scale magnetic features



Examples:

Active regions	month	50,000 km
Unipolar area	year	100,000 km
Activity cycle	22 years	700,000 km

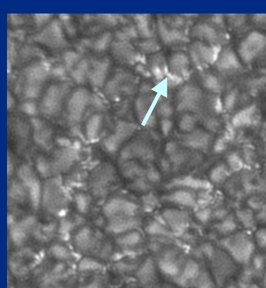
Properties:

Preferred latitude of emergence
Organized polarities (butterfly diagram)
Properties vary with solar cycle
Size > Rossby radius → Rotationally constrained
(~50,000 km)

Origin:

Manifestation of solar dynamo
Dynamo mechanism deep in the convection zone
Rotation -> breaks the spherical symmetry
transport of angular momentum
differential rotation
-> breaks reflectional symmetry
helicity, inverse cascade
large-scale magnetic fields

"Small" scale magnetic features



T. Berger, SVST

Examples:

Network	day	30,000 km
Inner network	min	limit of resolution

Properties:

No preferred latitudes
Mixed polarities
Can be found at any time during the solar cycle
Not rotationally constrained *(scales < Rossby radius)*

Origin, 2 possibilities:

1. By-product of the solar dynamo
   - decay of active regions
   - "noise" produced by the rise of active regions

2. Generated by local (surface) dynamo processes associated with convective motions:

- supergranules	10,000 km	day	→ network
- granules	1000 km	min	→ inner network

The theory of surface dynamo explores possibility 2.

Dynamo process

- Ingredients:
  - highly conducting plasma (magnetic field lines are frozen)
  - chaotic flow: any pair of neighboring points separate at exponential rate
  - Seed magnetic field → deformed at an exponential rate
- Competition between two exponentially growing processes:
  - Stretching of field lines → magnetic amplification
  - Increase of gradients and twisting-packing → increase of magnetic diffusion
- Vainshtain & Kichatinov 1986:
  - any turbulent (chaotic) flow is very likely to be a dynamo

Surface dynamo

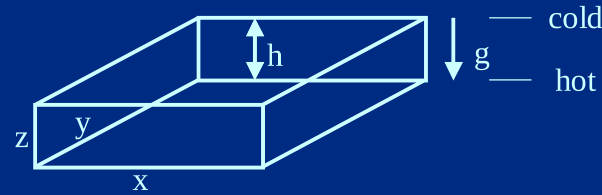
Hints:

- Solar plasma is highly conducting and the convective flows are expected to be turbulent:
  - Close to the surface: Rm = O(10^6) and η / ν = O(10^7).
- Correspondence between scales of convection and magnetic features
  - Granules min ~1000 km → inner network fields
  - Supergranules day ~20,000 -- 50,000 km → network fields

Ansatz:

- Part of the surface magnetic field could be generated locally by the thermally driven convective flow:
  - Meneguzzi & Pouquet 1989, direct simulation
  - Durney, De Young & Roxburgh 1993, low order closure
  - Petrovay & Szakaly 1993, observations and transport model
  - Schrijver et al. 1997, observations and statistical model
  - Cattaneo 1999, direct simulation
  - Emonet & Cattaneo 2001, direct simulation

Modeling



- Geometry:
  - Large aspect-ratio box: 10 x 10 x 1
  - Resolution: 512 x 512 x 97
- Boundary Conditions:
  - Top and bottom: at constant temperature and stress free
  - periodic in x and y
- Boussinesq Fluid, thermally driven turbulent (chaotic) convection
  - No compressibility
  - No ionization but high Re, Rm, chaotic flow
  - No radiative cooling

Equations

Boussinesq convection plus induction equation

$$(\partial_t - \nabla^2)\theta = -\partial_i(u_i\theta) + u_3$$

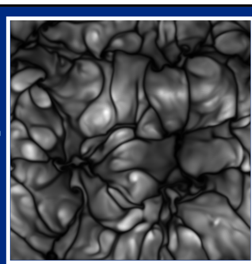
$$(\partial_t - \sigma\nabla^2)u_i = \partial_j(B_iB_j - u_iu - p\delta_{ij}) + Ra\sigma\theta\delta_{i3}$$

$$(\partial_t - \sigma/\zeta\nabla^2)B_i = \partial_j(u_iB_j - u_jB_i)$$

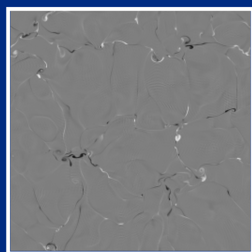
$$\theta, u_3, B_1,\ B_2,\ \partial_3 u_1,\ \partial_3 u_2,\ \partial_3 B_3 = 0 \ \text{at} \ z = 0,\ 1$$

Efficient dynamo

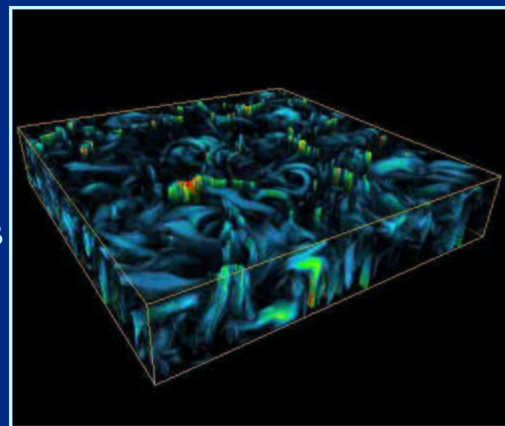
ΔT



Bz



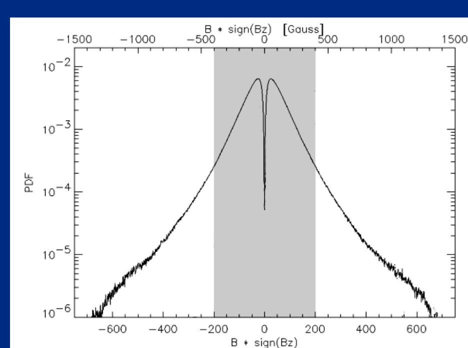
B



Ra	Size	ν / κ	ν / η	Pe	Re	Rm	B^2 / U^2	σ
500,000	10x10x1	1	5	200	200	1000	0.2	4.5
281,250	5x5x1	1	5	161	161	805	0.17	6.5
125,000	5x5x1	1	5	116	116	578	0.14	12.2
31,250	5x5x1	1	5	~60	~60	~300	not a dynamo	

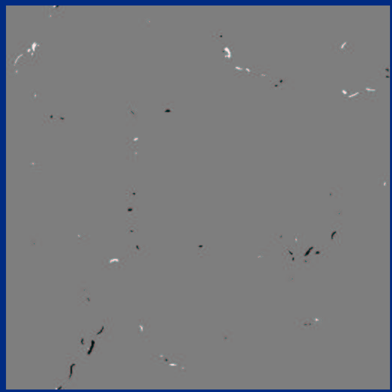
Strong magnetic fluctuations with a weak mean

- Exponential PDF
  - Not Gaussian like random process
  - Velocity has a Gaussian PDF
  - Velocity concentrates the magnetic field on the border of the convective cells
- Strong fluctuations (> 2 equipartition)
  - Small filling factor 0.3%
- Weak mean
  - flux density = ¼ equipartition
  - Permeates the whole volume
- Symmetric
  - Mixed polarities



Long lived (few overturning times) downflows attracting strong (> 2 equipartition) short lived magnetic concentrations

Life time similar to overturning time
Mixed polarities
Small filling factor: 0.3 %



|Bz| > 2 equipartition   10 overturns

Related observations

Magnetic flux in Quiet Sun does NOT vary with solar cycle (Harvey+White)

High resolution G-band observations (Berger & Title)

- Timescale for magnetic flux evolution in plage is ~ ***6-8 min***., morphological changes occur on timescales as short as ***100 sec.***
- ***No*** evidence of ***stable*** isolated subarcsecond flux tubes.

High resolution IR observations (Lin & Rimmele)

- Quiet Sun contains weak magnetic field (~ 1 G over 1 arcsec^2), mixed polarities.
- Evolves with the granular velocity field.

MDI/SOHO magnetograms (Hagenar, Schrijver, Title, …)

- Ephemeral regions are generated by convection; are not recycled cancelled flux.
- Quiet, mixed-polarity network is generated locally.

Hanle effect (Landi Degl'Innocenti, Stenflo, Trujillo Bueno, …)

- In the quiet photosphere there is a 5-15 G randomly oriented magnetic field.

MIcroStructured Magnetic Atmospheres, MISMA model (Sánchez Almeida)

- Consistent and unified reproduction of asymmetries in Stokes V profiles

Challenges for the theory

- Saturation of the dynamo process
- More realistic modeling
  - In our model $\nu / \eta = 5$, but in the convection zone $\nu / \eta << 1$
  - Effect of compressibility: SEE POSTER BY NORDLUND & STEIN
  - Compressible dynamo calculation in closed box, i.e. without influx of magnetic field.
  - Add radiative cooling
- Unified theory: put in a unique framework:
  - Large-scale, rotationally constrained solar dynamo
  - Small-scale, non-rotationally constraint fast dynamo
  - The difficulty: enormous ranges of spatial and temporal scales
- Direct comparison with observations

Challenges for the observation

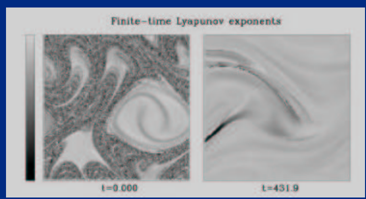
- Angular Resolution
  - Today the best angular resolution achieved are 0.2 arc sec ≈ 150 km:
  - Order estimates for Rm near the surface give Rm ≈ O(10^4 – 10^6)
  - Magnetic diffusive scales ≈ size of granule / Rm^(1/2) ≈ 10 km – 1km
  - Understand better what information is lost: use numerical result to test inversion methods?
- Resolution along the line of sight
  - Mean free path of a photon ≈ 100 km, i.e. Bigger than the magnetic diffusive scale
  - MISMA and non-MISMA approaches
- Comparison with theory: use PDF from simulations?

Conclusion

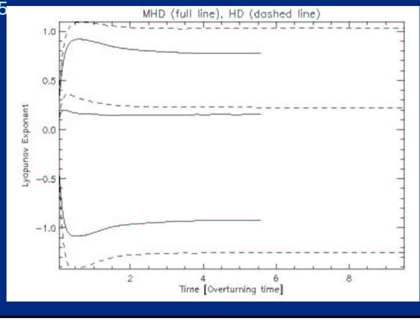
- Theoretical challenges
  - Saturation of the dynamo process
  - More realistic modeling
  - Unique framework for large- and small-scale dynamo: who is doing what?
  - More direct comparison with observations
- Observational challenges
  - Angular resolution
  - Understanding the effects of limited resolution along the line of sight
  - Comparison with theory: use PDF from simulations?

Saturation by suppression of chaos?

- Cattaneo, Hughes and Kim (1996). Forcing + inertia neglected:
  - Forcing with: U = (∣y ∇, - ∣x ∇, ∇) and ∇ =[sin(x+cos t)+cos(y+sin t)] sqrt(3/2)
  - Kinematic regime: large regions of chaos
  - Saturation: most regions of chaos are suppressed
  - Lim log(x(t) / x0) / t
    t



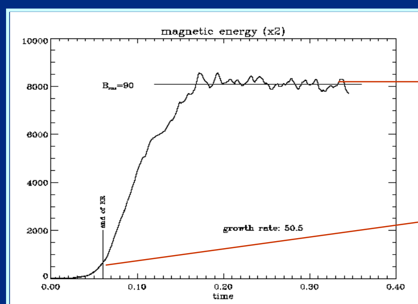
- Using the fully non-linear 3D Boussinesq Eqs.
  - Compare the finite time Lyapunov exponents in the saturated dynamo: Re=200, Rm=1000, Ra=500,000, ⌊/⌊=1, ⌊/⎝=5
  - with the non-magnetized case: Re=250, Ra=5 10^5, ⎧ = ⌊/⌊=1
  - 128 x 128 particles followed during 6 to 10 overturning times

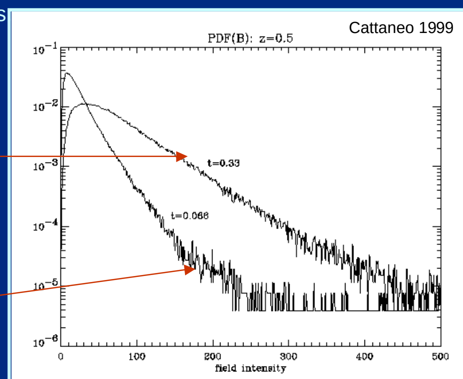


- Answer: not clear!

Saturation: related to the fraction of the volume available for packing magnetic field

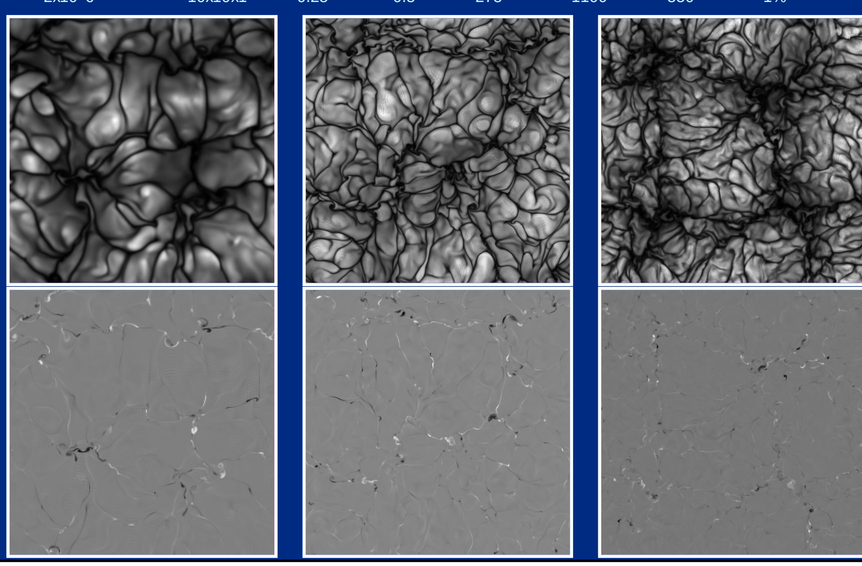
- For a given convective flow, there is a limited fraction of the volume where magnetic field can be accommodated.
- Between the end of the kinematic regime and the beginning of the saturated regime this fraction of the volume gets filled up with magnetic energy.
- Maximum B reached during the kinematic phase. Saturation happens by populating the equipartition levels

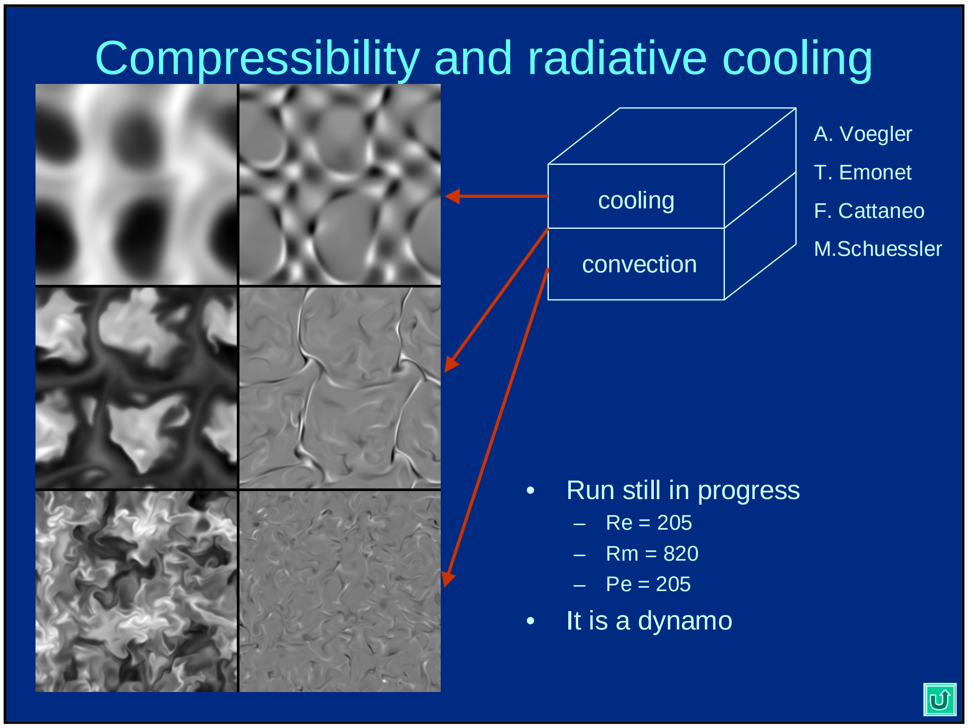


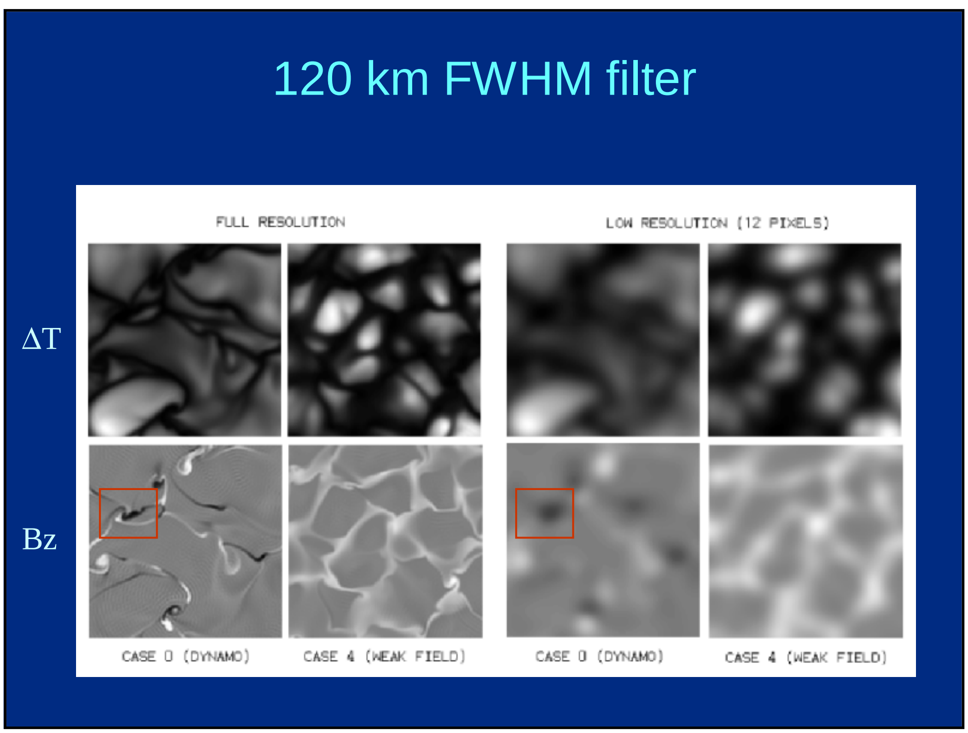


Adjust κ to keep large spatial scales in the driving force: ν<μ<κ

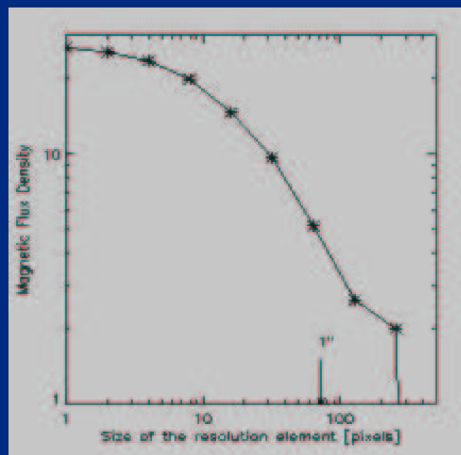
Ra	Size	ν / κ	ν / η	Pe	Re	Rm	B^2 / U^2
5x10^5	10x10x1	1	5	200	200	1000	20%
4x10^6	10x10x1	1	1	565	565	565	6% growing
2x10^6	10x10x1	0.25	0.5	275	1100	550	1%




Compressibility and radiative cooling
cooling
convection
A. Voegler
T. Emonet
F. Cattaneo
M.Schuessler
• Run still in progress
– Re = 205
– Rm = 820
– Pe = 205
• It is a dynamo


120 km FWHM filter
FULL RESOLUTION
LOW RESOLUTION (12 PIXELS)
ΔT
Bz
CASE 0 (DYNAMO)
CASE 4 (WEAK FIELD)
CASE 0 (DYNAMO)
CASE 4 (WEAK FIELD)

Flux density



With 1” resolution and a good sensitivity, only 10 % of the actual flux is measured