MHD Numerical Simulations of dynamo action

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Overview

Introduction

- The dynamo problem
- Astrophysical examples
- Mathematical approach

Types of Dynamos

- Kinematic
- Non-linear, Turbulent
- Similarities, Differences

Nature of dynamos

- STF + (R) process
- Week field importance
- ‘Generic’ behaviour

The dynamo problem

Considerations

- Conditions for dynamo action
- Types of flows
- Amplification mechanism

Astrophysical examples

Solar Dynamo

22-year cycle
Sunspot activity
Turbulent motions (CZ)

Earth Dynamo

Decay time ~ 150.000 y
Activity ~ 100 mil.y

Planets

Jupiter
Mercury
Mars, Venus

Mathematical treatment

- MHD approximation:

  - Interaction of magnetic fields with fluid motions

- The simplest formulation – induction equation:

$$\partial B/\partial t - \nabla\times(u\times B) - \eta\nabla^2 B = 0$$

- Dominance of transport over diffusion:

$$Rm = u\, L/\eta \equiv \text{Magnetic Reynolds number}$$

- Theory and simulations:
  - The perfectly conducting limit ($Rm \rightarrow\infty$), relevant to astrophysics.
  - Alternative : Invariant properties of the flows and/or of magnetic transport.

Kinematic Dynamo Theory

Velocity (prescribed) and magnetic fields are decoupled. The Lorentz force is neglizible. The question is : What types of flows in the induction equation give solutions of the form of growing eigenfuctions.

Fast/Slow Dynamos

Fast (slow) dynamos are dynamos with positive (negative) and finite growth rate when the resistivity goes to zero. There is strong evidence that many types of chaotic flows give rise to fast (kinematic) dynamos.

Direct dynamo action

Evidence from numerical experiments indicate that dynamo action is 'direct' with growth rates of the order of a few turn-over times on the sytem scale. More about this below.

Non-Linear Dynamos

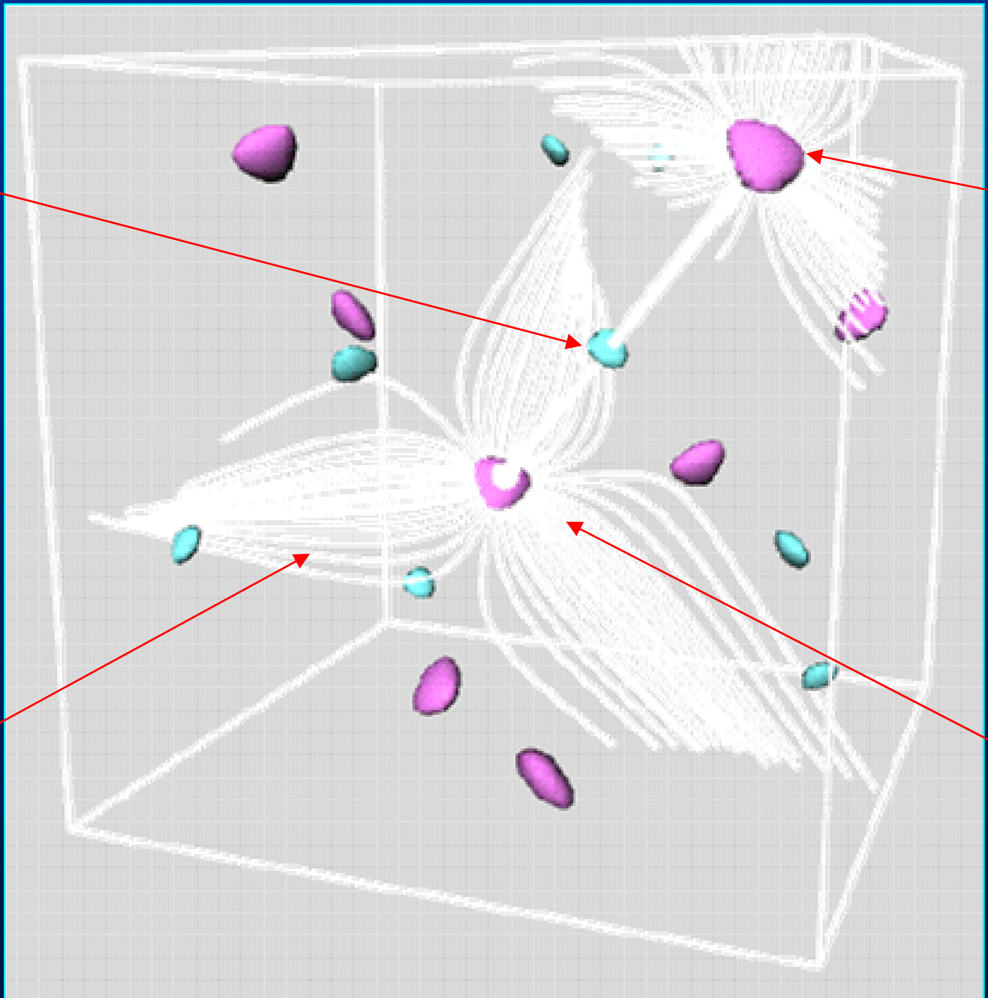
In real life, the structure of magnetic field must be determined by the coupled system of the field and flow (Lorentz force). It is important to understand not only the process that leads to the amplification of the field but also the process by which it stops growing, since it is the balance between that eventually determine the structure of the observed magnetic fields. Cosmic dynamos must be in the non-linear rather than in the linear state.

Turbulent Dynamos

Traditionally, turbulence was thought to be essential to dynamo action. There is new evidence that indicates that laminar and turbulent dynamos are surprisingly similar, with growth rates similar to large scale turn-over times in both cases.

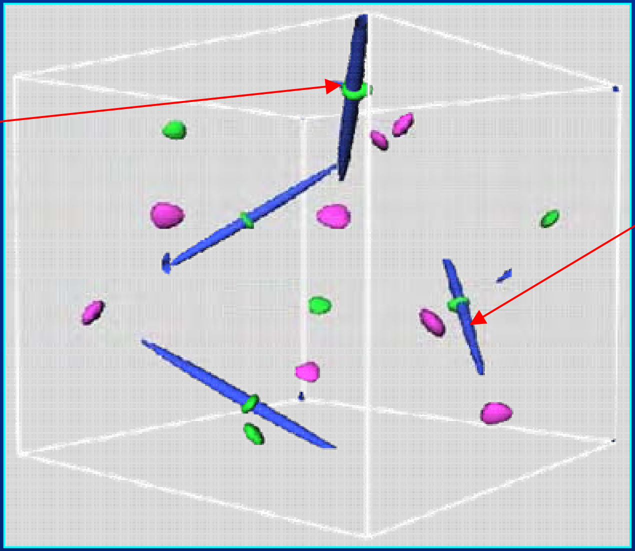
Chaotic ABC flows

$$U_x = B\cos(ky) + C\sin(kz)$$
$$U_y = C\cos(kz) + A\sin(kx)$$
$$U_z = A\cos(kx) + B\sin(ky)$$



Visualization of Magnetic fields

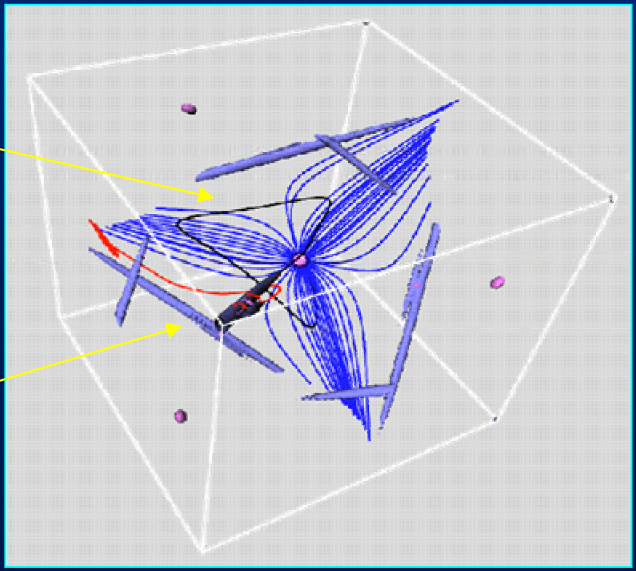
Alpha-type stagn.points



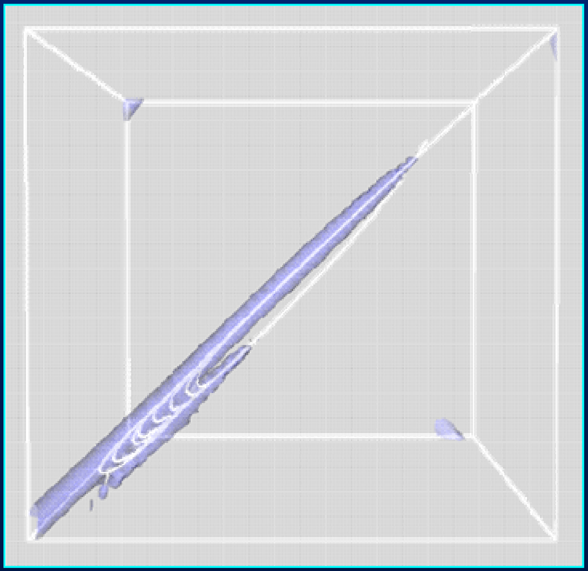
Magnetic Flux cigars

Reconnection

Magnetic field line

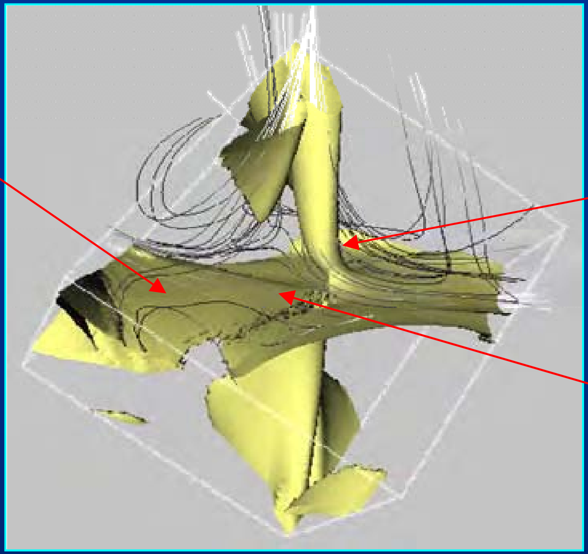


Double Flux cigars



Fast dynamo action

Flux sheets

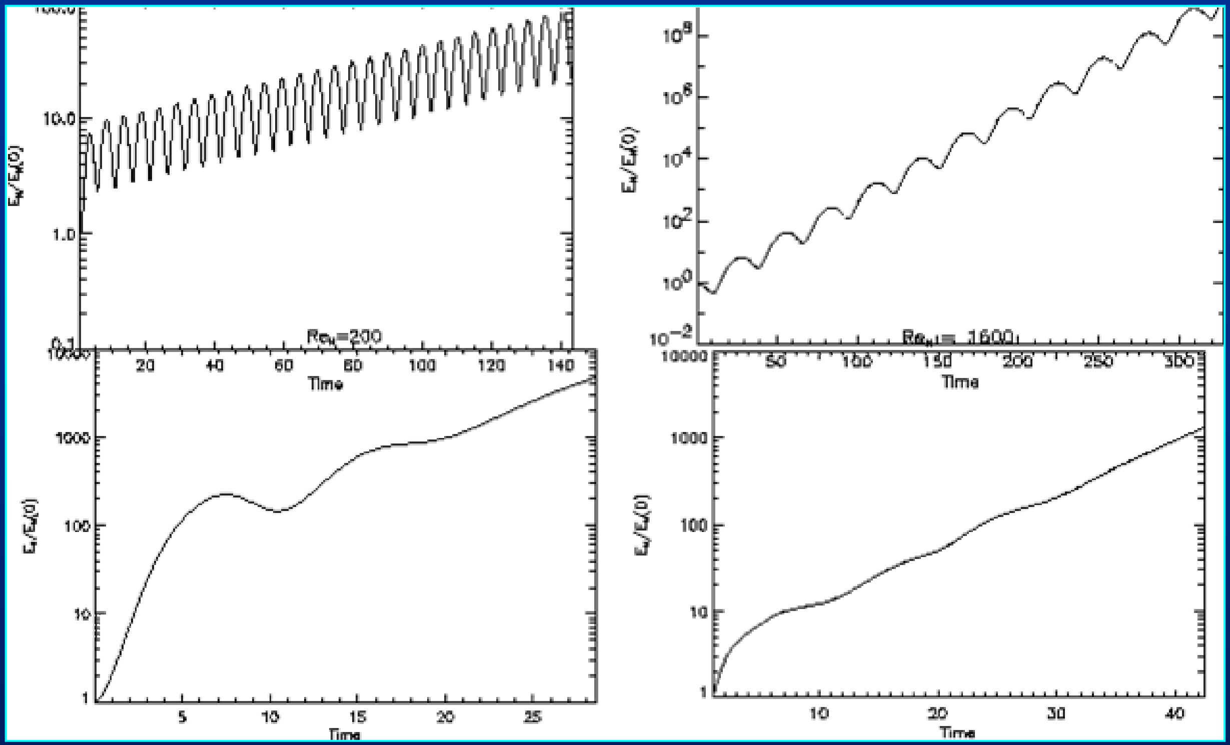


Folding of the week B

Plane of the Beta-type

- Simple geometry of flow eigenvectors
- Relatively simple magnetic field geometry
- Understandable scaling properties when $Rm \rightarrow \infty$
- Structures just scale with $1/\sqrt{Rm}$
- It is a steadily growing dynamo

Magnetic energy and growth rates



•Growth rate ~ 0.07 ~ 1/(about 4 t.o)

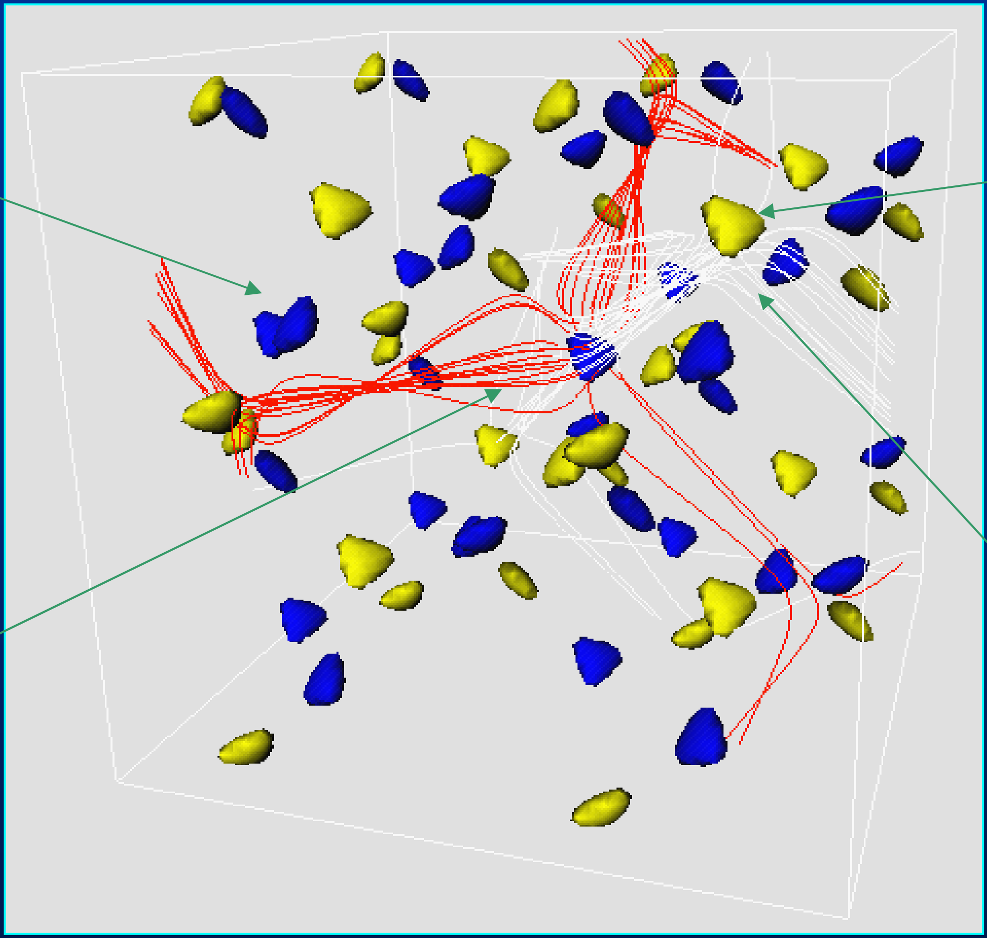
•Invariant properties of the flow as Rm→∞

•Very strong physical/geometrical arguments for 'fast' dynamo action

Make it more difficult…(k=2)

A-type stagn.points

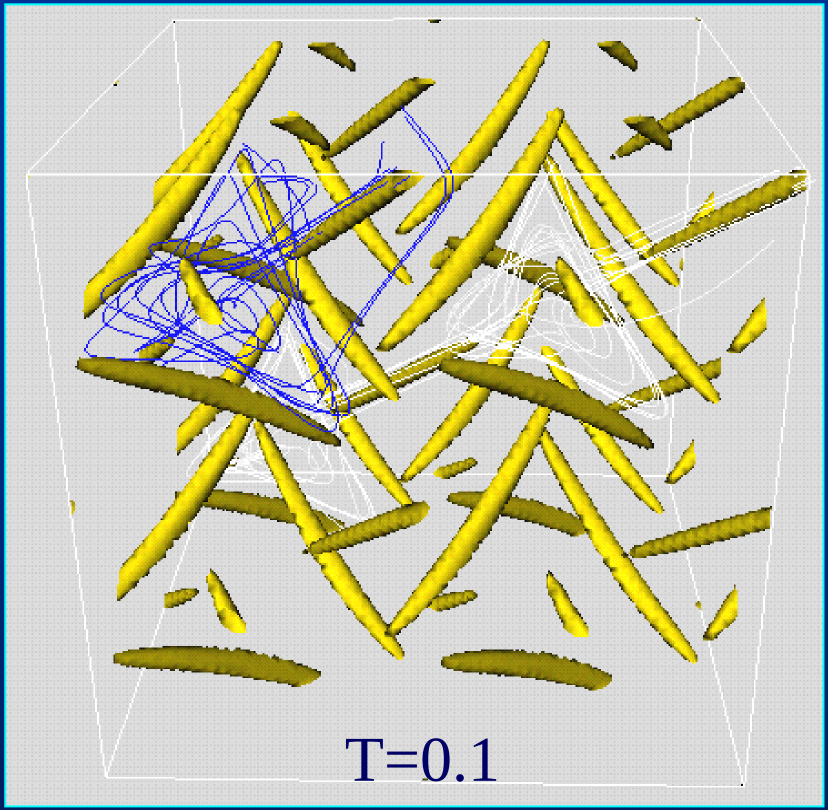
B-type stagn.points

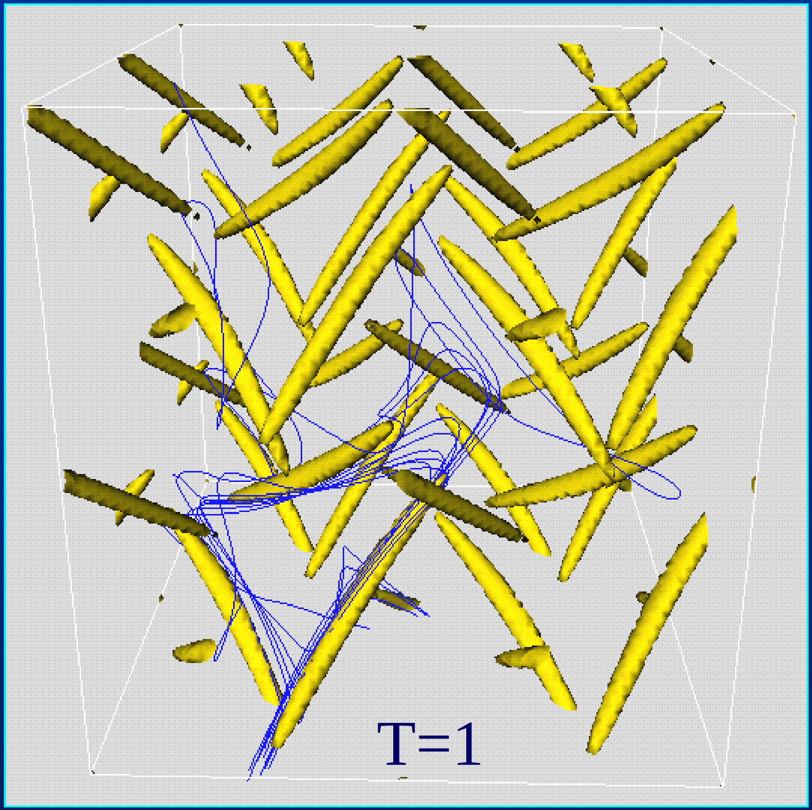


Converging streamlines

Diverging streamlines

Magnetic Structures

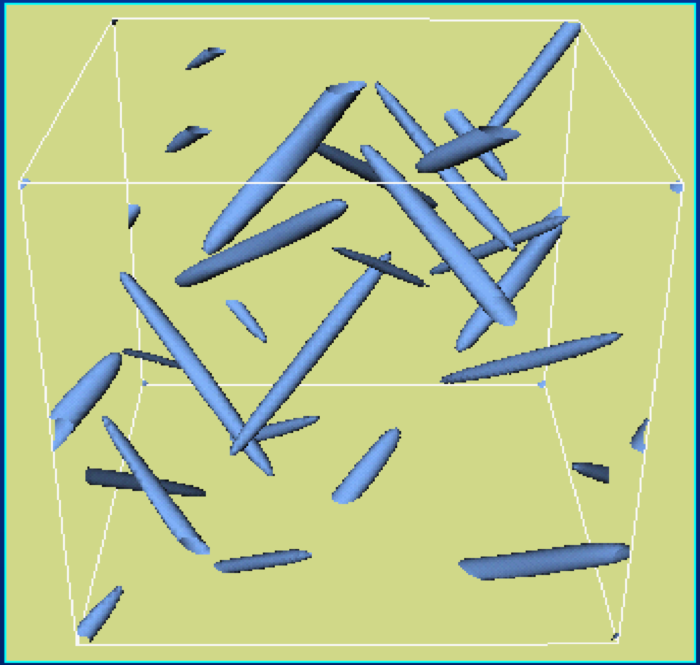




- Initial, same ‘recycle’ of the field - strong symmetry
- T=1.5, transportation of the week ‘loose’ field from cell to cell because of the breaking symmetry of the fastest growing eigenmode (magnetic field)
- Growth rate ~ 0.3*k/2 (for k>2)

Conclusions - Kinematic dynamo

Fastest growing eigenmode



Breaking of symmetry

• ABC flows are ideal for studying how dynamos work.

• They produce fast dynamo action whatever the values of parameters, such as Rm or k, are. Most of space has passive advection and main properties of u and B do not change.

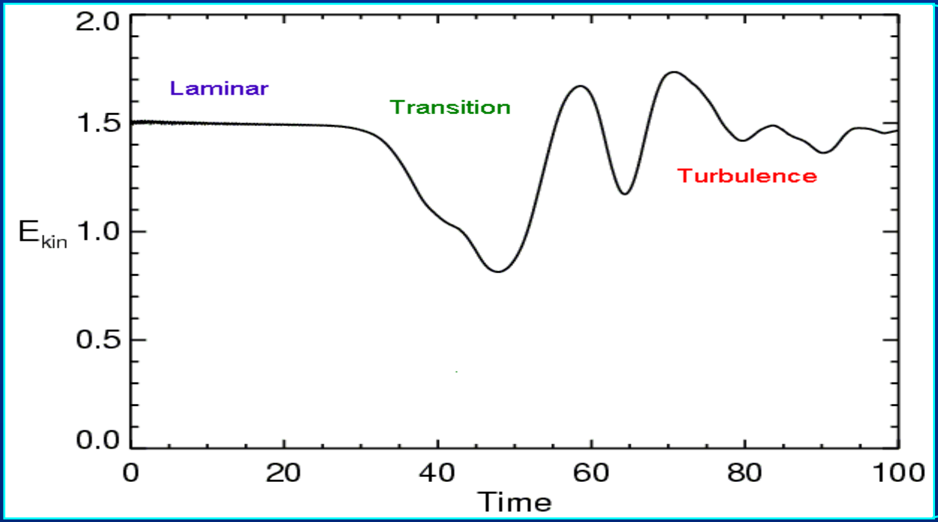
• The mechanism that drives the dynamo is the same : stretching of the weak part of the field.

Non-linear Dynamos

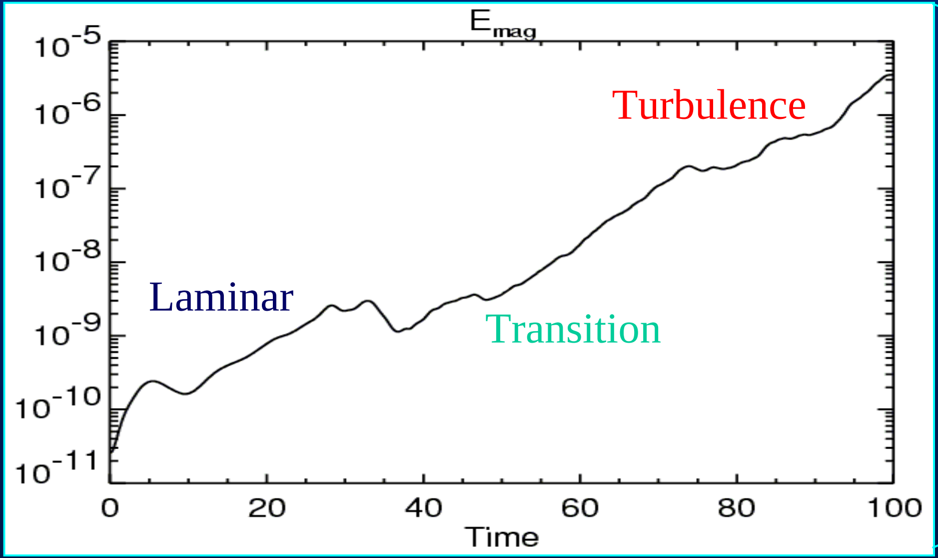
The exponential growth of the magnetic field stops and saturation occurs through the Lorentz force.

- Run experiments using the ‘normal’ ABC flow which becomes unstable for Re>13 and turbulent for higher Re.
- Forcing is needed to keep it’s original form at least in the kinematic regime for small Re and before turbulence kicks in.
- Use of fully compressible MHD equations, taking the Lorentz force into account.
- Keep Re=Rm (~100 to 1000) and A=0.9, B=1 and C=1.1 because turbulence develops faster.
- Numerical resolution up to 128^3.
- Parallel supercomputing, CM-Fortran, 3D volume rendering visualization techniques.

Results

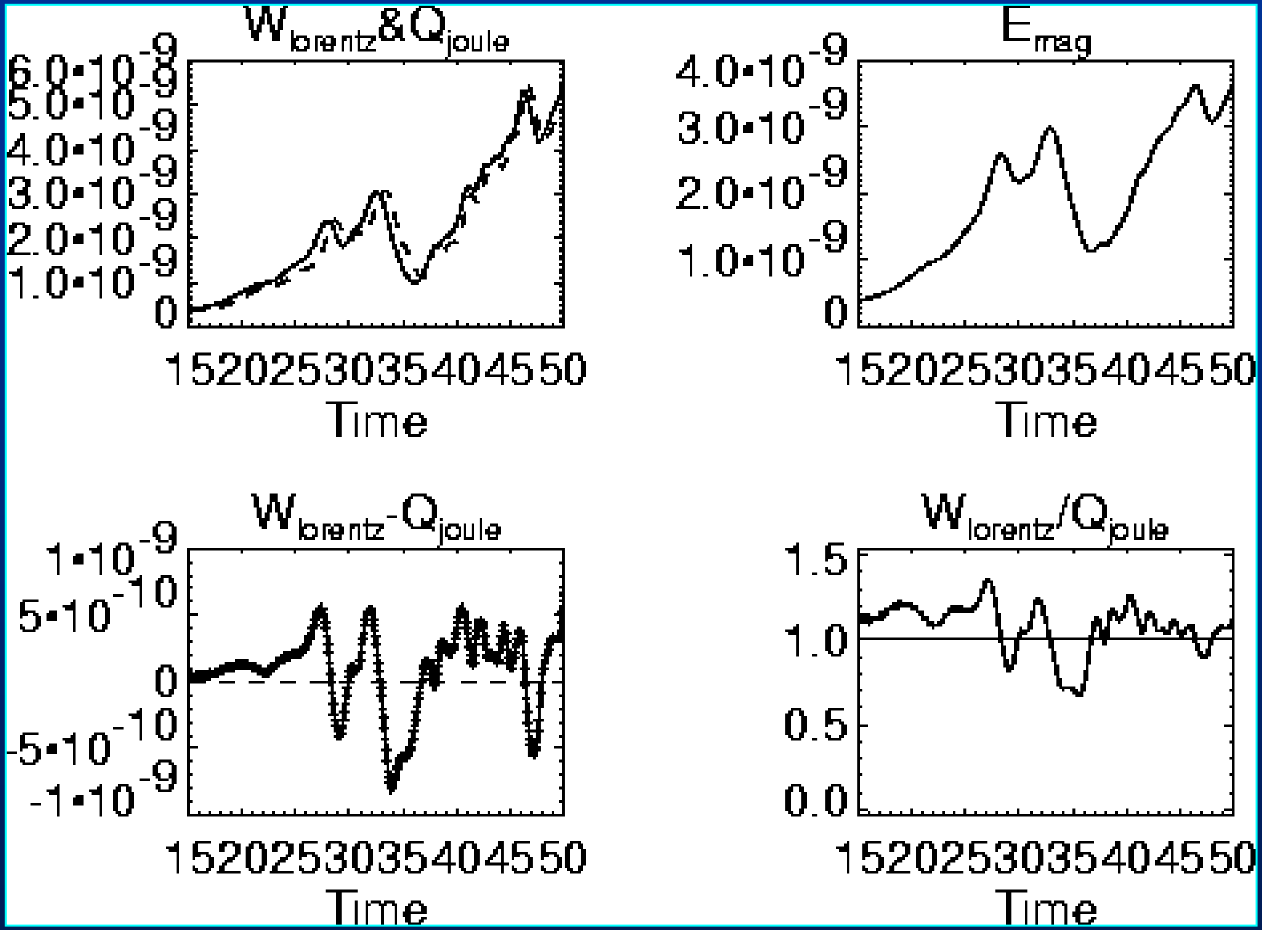


The kinetic energy level has to be maintained (close to the nominal value of Eo) by external forcing in order to have constant Re during the simulation.

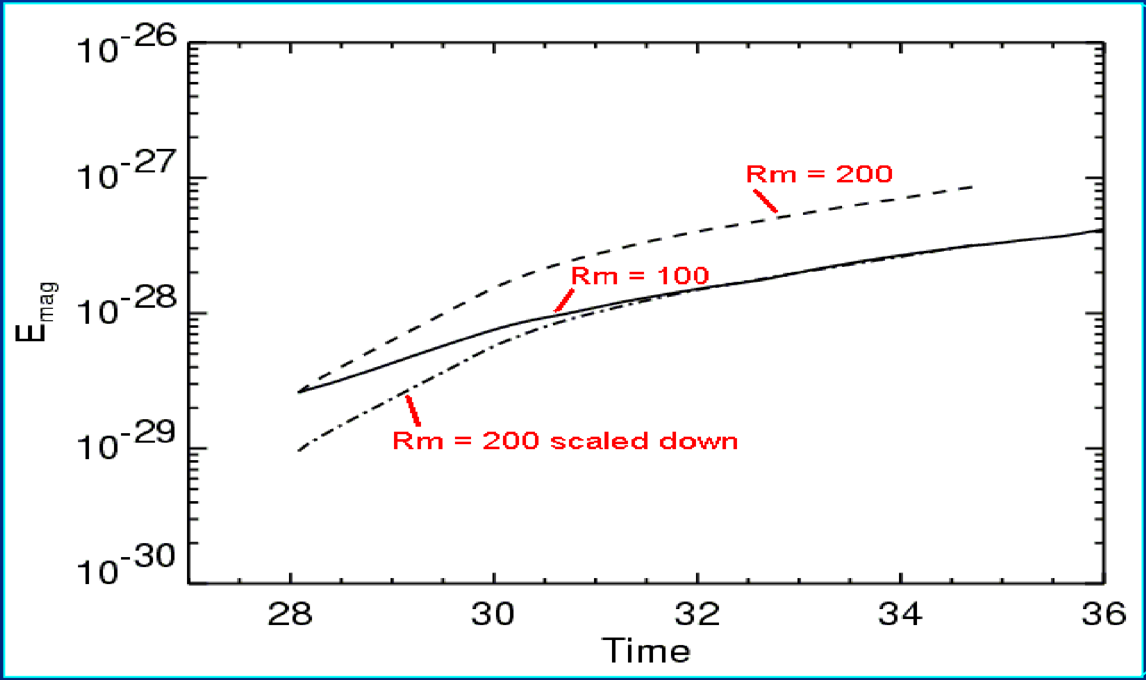


The magnetic energy rate of growth is 0.15 during the laminar phase and remains the same after a transition phase and when the flow enters the turbulent regime.

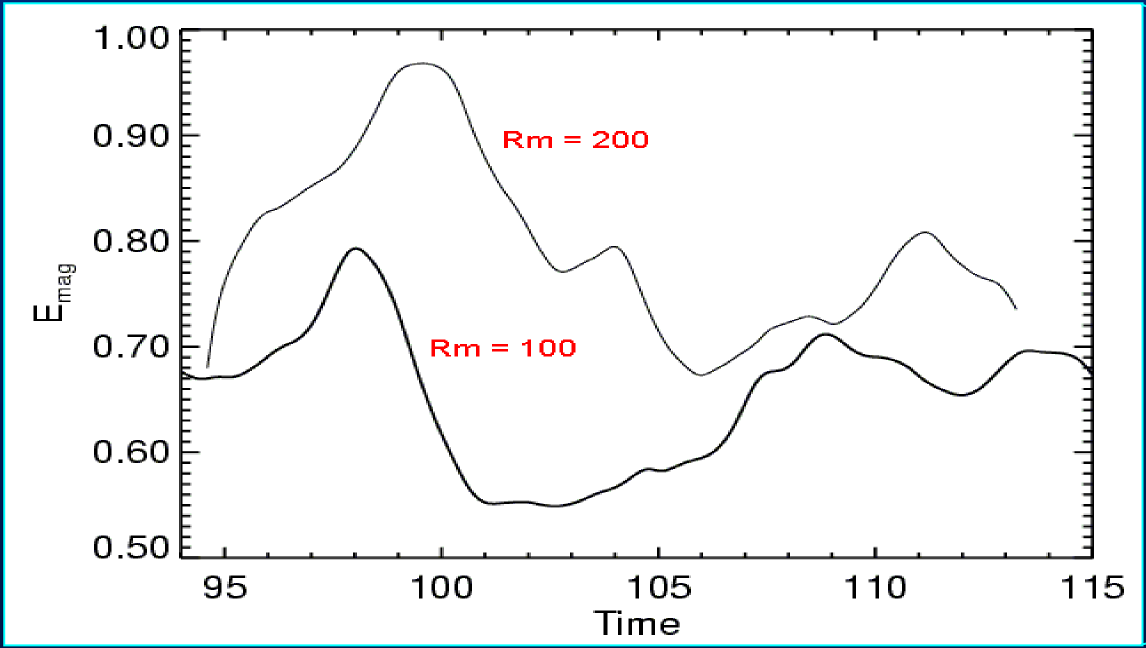
Balance of Work and dissipation



- Detailed balance between Wl and Qj.
- Accuracy on numerical results and the equations of energy budget.

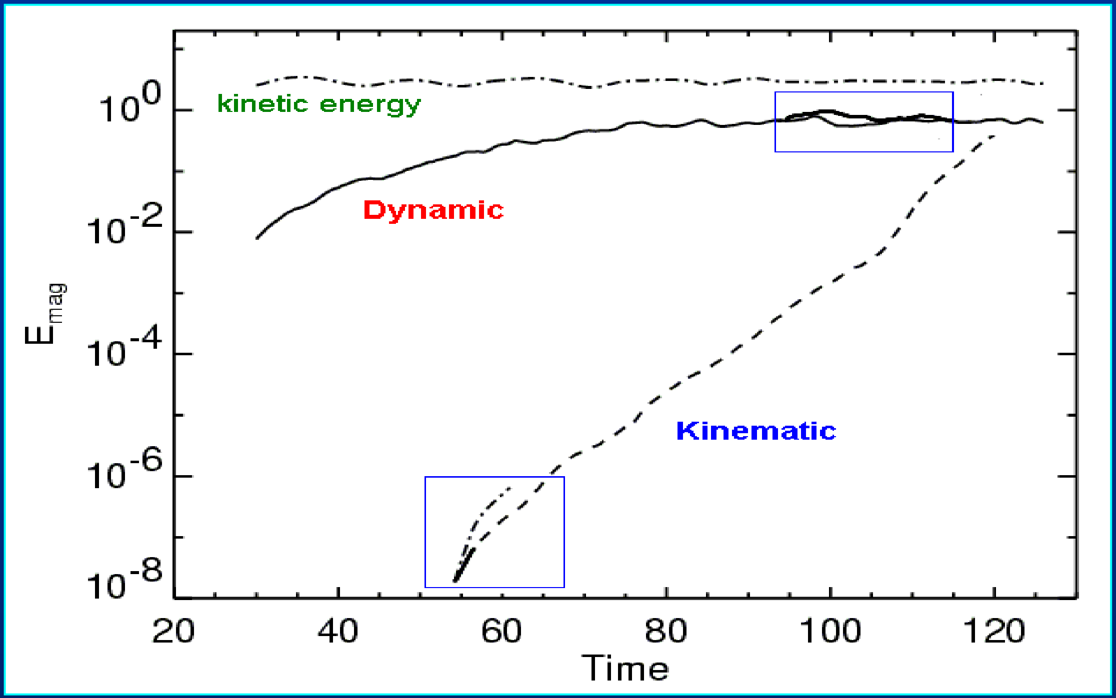


The initial difference in the magnetic energy amounts to a factor of 2.7. The growth rates are very similar !. The numerical resolution is 80^3 (Rm=100) and 160^3 (Rm=200).



The overall level is slightly higher (but less than 2.7) and the evolution is slightly delayed for the higher Rm case. There is also more time structure in the high Rm case.

Kinematic growth, Dynamic saturation



- <u>Kinematic phase :</u> The growth rate is independent of Rm

•Changing Rm causes a transient change – thinner structures –larger Emag

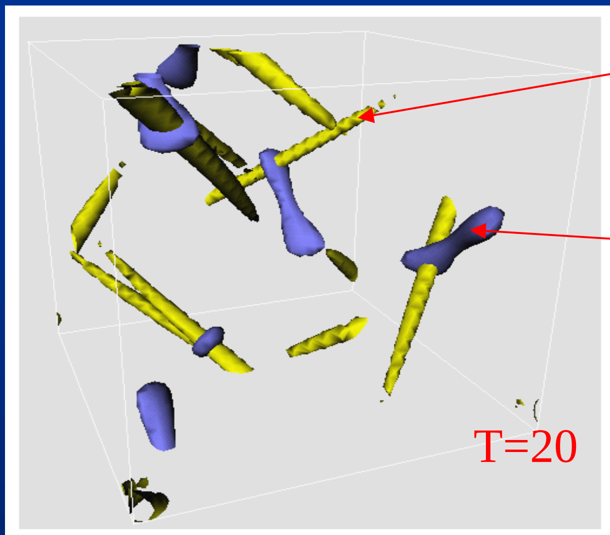
•<u>Dynamic phase :</u> Changing Rm causes a much weaker change

•Thinner structures prevented

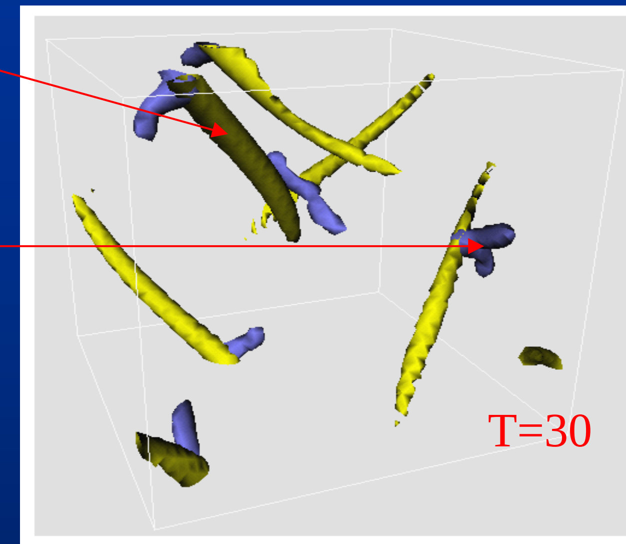
- Size determined by Lorentz force, not by diffusion

Visualization of isosurfaces

Laminar



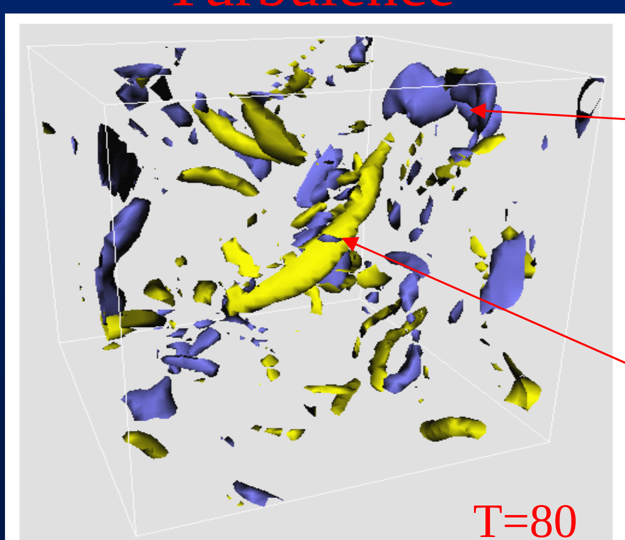
Disturbance



Flux ‘cigars’

Stagnation points (disturbed)

Turbulence



Stagnation points have disappeared

The magnetic field has an intermittent configuration. Flux sheets become prevelant.

Work and dissipation

Spatial separation

High Dissipation regions (e.g more than 0.1% of max dissipation)

- Thin flux structures (“cigars”) with high B
- Very small volume filling factor
- Scale as $1/\sqrt{Rm}$
- Magnetic diffusion significant

Low Dissipation regions

- Flux sheets with low B
- Nearly space - filling
- Passive advection of magnetic field lines
- Magnetic diffusion insignificant

Nature of the dynamo:Pure work

REMEMBER (from the previous non-linear experiments): in the generic turbulent dynamos there is a close balance between the Lorentz work and the Joule dissipation even in the saturation regime. However the work is much less noisy when the velocity is prescribed and / or has not yet enetered the turbulent phase.

Final experiment

- Kinematic dynamo action, using standard ABC flow with Rm=300.
- Compute Joule work and Ohmic dissipation – well defined even in kinematic cases !!
- Advantage : No ‘flexing’ of moving magnetic structures.
- Heart of the problem : Where and how the dynamo works ? Is the above mentioned balance “sensitive” ?

Striking results

Average Joule dissipation	326.3
Average Lorentz work	271.1
Average magnetic energy	332.3
Energy growth rate	0.166
Fractional dissipation level	0.0012
Fractional volume	0.89
Net work in weak dissipation regime	55.1
Net work in high dissipation regime	0.09

There is an almost perfect balance in the high dissipation regions

- The volume with dissipation above 0.1% of the maximum fills 10% of the volume
- The dissipation there is almost perfectly balanced by local work
- More than 99.5% of the dissipation and less than 0.2% of the net work occurs there

There is almost pure work (very little dissipation) in the rest of the volume

- The low dissipation region covers 90% of the volume
- Less than 0.5% of the dissipation occurs there
- 99.8% dynamo (net) work occurs there

Conclusions

- Dynamo work occurs by passive ‘pure’ stretching.

- Most of the dissipation is unrelated to the dynamo process – it is in detailed balance by local work.

- The growth rate is determined by the large scale properties of the flow (in cases where large scale flows dominate e.g Sun) → e-folding times ~ a few turn-over times (the exact factor depends on the flow topology).

- Growth rates are similar for laminar and turbulent case (provided they have similar large scale topology) and saturation levels are independent of Rm and Re (when sufficiently large).

- Both cases reflect the same mechanism at work : stretching of the initial weak part of the magnetic field.

Applications

- Quiet Sun photospere: Numerical experiments, based on the recent advances in the theory of fast dynamos, study the possibility that a substantial fraction of the magnetic field is generated locally by dynamo action driven by the turbulent velocities associated with the granular and supergranular flows (F.Cattaneo-Chicago University, Ake Nordlund – Niels Bohr Institute).

- Understanding of dissipation : in magnetically dominated near-by turbulent plasmas driven by boundary motions. Solar corona - flares and heating are being generated by shearing of the coronal magnetic field by motions in the much denser solar atmosphere). (K.Galsgaard-St.Andrews University).

- Dynamics : Supercomputer windows into the formation and evolution of flux tubes, vortex tubes, electrical current sheets, MHD shocks (B.Dorch – Stockholm Observatory).

- MHD/Turbulence : under the more extreme conditions characteristic of the cold molecular clouds found in star formation regions (P.Padoan – Harvard University).