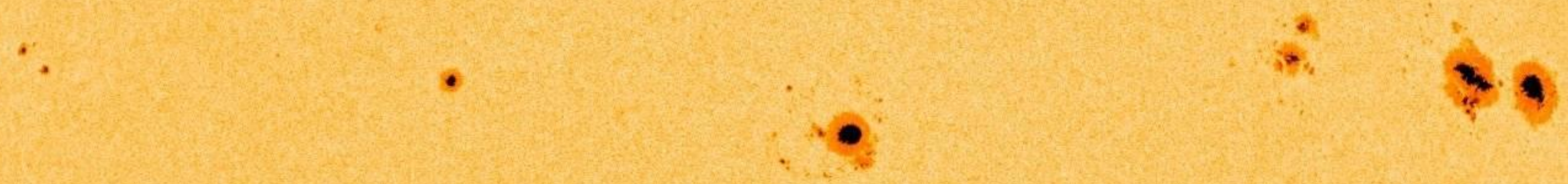
What causes downflows in magnetic flux concentrations?

Axel Brandenburg (Nordita/Stockholm)



Downflows ←→ spot formation
Seat of dynamo
Mean-field description (predictive understanding)
Analogy between NEMPI and dynamo instability
Really NEMPI

THE FORMATION OF SUNSPOTS FROM THE SOLAR TOROIDAL FIELD*

EUGENE N. PARKER
Department of Physics, University of Utah, Salt Lake City, Utah
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To obtain a quantitative estimate of the buoyancy force, consider a flux tube of 100 gauss at a depth of 2×10^4 km in the sun. At this level $\rho_e \cong 2.5 \times 10^{-4}$ gm/cm^3, $T_e \cong 2.5 \times 10^5$ K. Equation (5) gives $\rho_e - \rho_i \cong 2 \times 10^{-11}$ gm/cm^3, which is only 10^{-7} of the density ρ_e. A temperature variation of 0.02 K would produce the same fluctuation in the density. We see, then, that magnetic buoyancy will be negligible for the general solar field. Consider, however, a relatively intense strand of field of, say, 10^3 gauss, produced by an abrupt shearing in the turbulent convective motions at a depth of only 10^3 km. Now $\rho_e \cong 0.8 \times 10^{-8}$ gm/cm^3 and $T_e \cong 1.5 \times 10^4$ K; equation (5) gives $\rho_e - \rho_i \cong 3 \times 10^{-8}$ gm/cm^3. Hence $\rho_e - \rho_i$ is now 0.04 ρ_e and is equivalent to heating the region by 600° K; if the rope is not swept back down into the convective zone by some violent convective flow, it will rise to the surface of the sun.

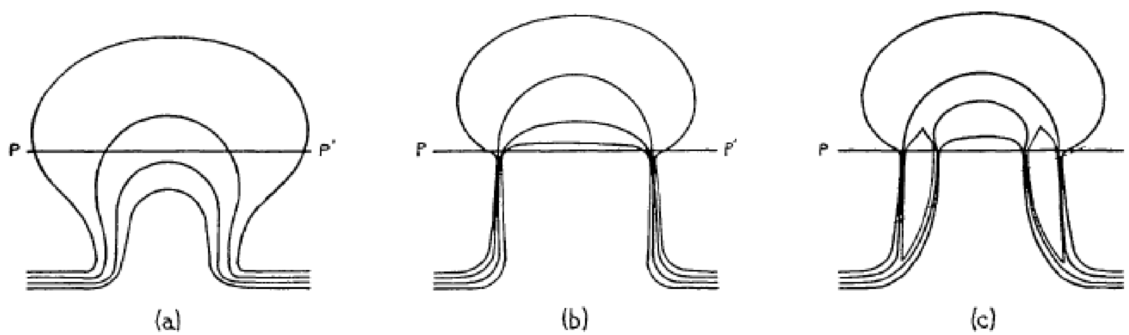

FIG. 2.—The development of a toroidal flux tube into a sunspot. *a*, indicates in a rough way how the tube might look after being borne to the surface by the magnetic bouyancy; *b*, shows the concentration just under the photosphere due to cooling; *c*, indicates splitting of the tube as a consequence of the abrupt tapering above the cool region.

Need for hydraulics

HYDRAULIC CONCENTRATION OF MAGNETIC FIELDS IN THE SOLAR PHOTOSPHERE. VI. ADIABATIC COOLING AND CONCENTRATION IN DOWNDRAFTS*

E. N. PARKER
Department of Physics and Department of Astronomy and Astrophysics, University of Chicago

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ABSTRACT

The remarkable concentration of the general field of the Sun into isolated intense flux tubes at the visible surface must be a direct consequence of conditions immediately beneath the surface. It is pointed out that the convective heat transport in the magnetic field swept into the downdrafts in the junctions of supergranule boundaries is strongly suppressed by the magnetic field. The net heat transport is reduced to such a degree that the temperature of the downdraft within the field increases nearly adiabatically below the visible surface, and hence is significantly cooler than the surrounding ambient gas. The reduced temperature enhances the downdraft within the field and permits the gravitational field to evacuate the flux tube. The magnetic field is then strongly compressed by the external gas pressure, leading to the extraordinary observed strengths of 1500 gauss or more. It is suggested that the magnetic knots found in active regions are formed wholly or partly by the same effect.

Near-surface concentration ← → deeply roted tubes

Sunspots from downdrafts

SUNSPOTS AND THE PHYSICS OF MAGNETIC FLUX TUBES. VII. HEAT FLOW IN A CONVECTIVE DOWNDRAFT[1]

E. N. PARKER
Department of Physics and Department of Astronomy and Astrophysics, University of Chicago
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ABSTRACT

The heat flux in the familiar Boussinesq convective cell with free upper and lower boundaries is plotted to show the suppression of the upward heat flow by a downdraft. Application to the solar convective zone shows that downdrafts of 1–2 km s^{-1} at depths of 1–4 × 10^3 km beneath the visible surface of the Sun are sufficient to reduce the upward heat flux to a small fraction of the ambient value. Hence the downdraft that is postulated to operate beneath the sunspot, to account for the gathering of flux tubes to form the spot, would be sufficient to reduce the heat flux to values comparable to those observed in sunspot umbrae. This greatly relieves the demands on cooling by the convective generation of Alfvén waves in order to form the observed intense fields of 3000 gauss or more.

As a final comment, then, we emphasize that the subsurface downdraft to which we appeal (Parker 1979*a*) for the bunching of flux tubes to form a sunspot remains an hypothesis, neither supported nor contradicted by the fluid motions observed at the surface of the Sun. The outflow that sometimes appears at the outer edge of the

On Buoyant Magnetic Flux Tubes in the Solar Convection Zone

M. Schüßler

Universitäts-Sternwarte, Geismarlandstr. 11, D-3400 Göttingen, Federal Republic of Germany

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Move to the bottom of CZ

vertical velocities are always of the order of a few meters per second, causing timescales of the order of the solar cycle for the rising through the whole convection zone. Thus there is enough time for the fields to be amplified by a differential rotation and α-effect in order to build up an $\alpha\omega$-dynamo.

THE GENERATION OF MAGNETIC FIELDS IN ASTROPHYSICAL BODIES. X. MAGNETIC BUOYANCY AND THE SOLAR DYNAMO*

E. N. Parker

Department of Physics and Department of Astronomy and Astrophysics, University of Chicago

Received 1974 September 20; revised 1974 November 25

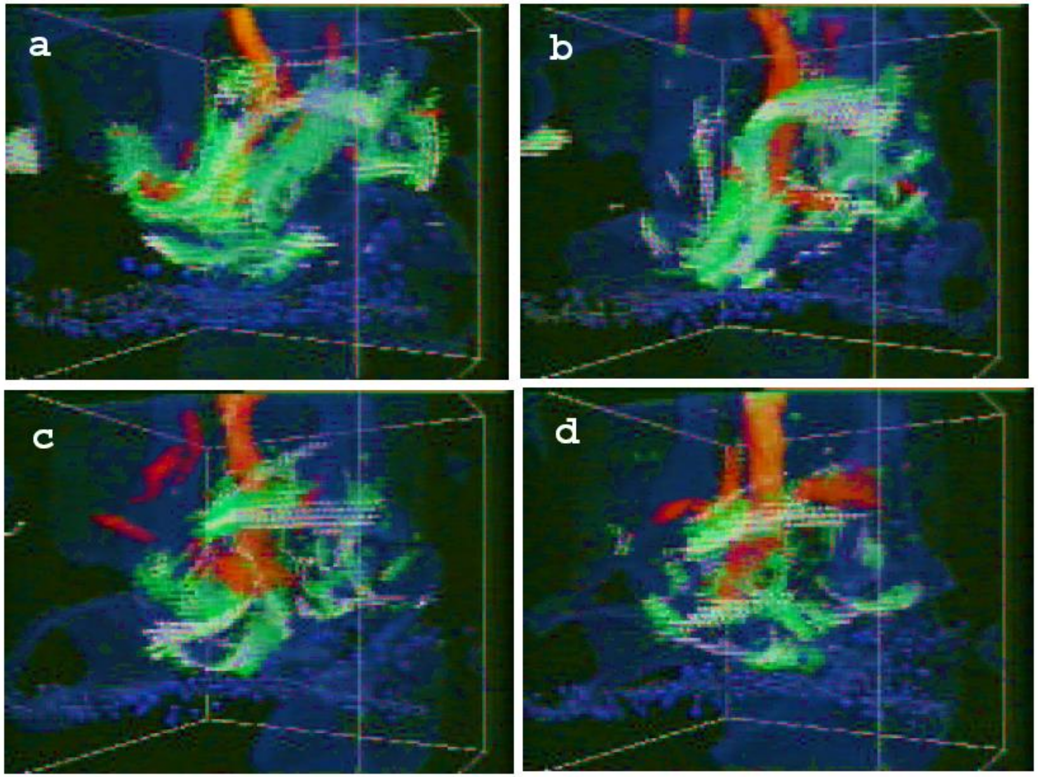
ABSTRACT

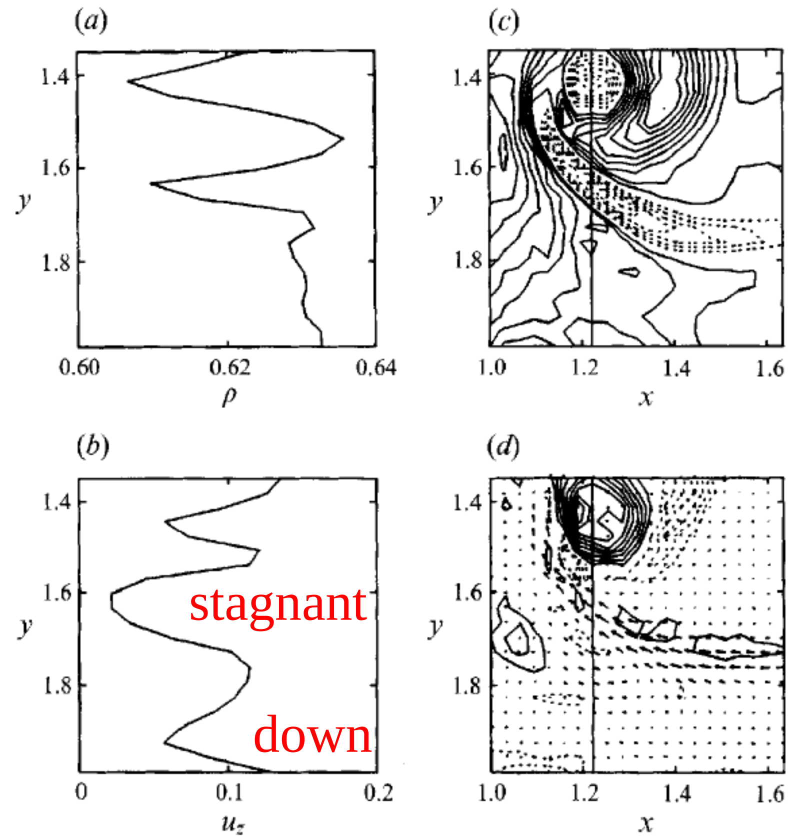
The magnetic field appearing as bipolar magnetic regions at the surface of the Sun represents the lines of force from a general azimuthal field of the order of 10^2 gauss somewhere beneath the surface. The amplification time, as a consequence of the nonuniform rotation, is of the order of 10 years. But magnetic buoyancy brings the azimuthal field up through much of the convective zone in a time rather less than 10 years, raising the question of where the azimuthal field can be retained long enough to be amplified.

We show that magnetic fields can be retained for long periods of time in the stable radiative region beneath the convective zone, but unfortunately the solar dynamo cannot function there because turbulent diffusion is an essential part of its operation.

The only possible conclusion appears to be that the dynamo operates principally in the very lowest levels of the convective zone at depths of 1.5×10^5 km or more, where the gas density is 0.1 g cm^{-3}, and the fields are limited to 50 gauss, rather than the usually estimated 10^2 gauss.

magnetic buoyancy not a problem





Stratified dynamo simulation in 1990
Expected strong buoyancy losses,
but no: → downward pumping

Brandenburg et al. (1996)

Cosmic Magnetic Fields:
From Planets, to Stars and Galaxies
Proceedings IAU Symposium No. 259, 2008
K.G. Strassmeier, A.G. Kosovichev & J.E. Beckman, eds.

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Paradigm shifts in solar dynamo modeling

Axel Brandenburg
Nordita, Roslagstullsbacken 23, 10691 Stockholm, Sweden

Abstract. Selected topics in solar dynamo theory are being highlighted. The possible relevance of the near-surface shear layer is discussed. The role of turbulent downward pumping is men-

Helioseismic Constraints and Paradigm Shift in Solar Dynamo

Alexander G. Kosovichev[1], Valery V. Pipin[1,2,3], and Junwei Zhao[1]
[1]*Stanford University, Stanford, CA 94305, USA*
[2]*UCLA, Los Angeles, CA 90095, USA*
[3]*Institute of Solar-Terrestrial Physics, Irkutsk, 664033, Russian Federation*

generated near the bottom of the convection zone, in the tachocline. However, there is a number of theoretical and observational problems with justifying the deep-seated dynamo models. This leads to the idea that the subsurface angular velocity shear may play an important role in the solar dynamo. Using helioseismology measurements of the internal rotation and meridional circulation, we investigate a mean-field MHD model of dynamo distributed in the bulk of the convection zone but shaped in a near-surface

THE CASE FOR A DISTRIBUTED SOLAR DYNAMO SHAPED BY NEAR-SURFACE SHEAR

AXEL BRANDENBURG
Isaac Newton Institute for Mathematical Sciences, 20 Clarkson Road, Cambridge CB3 0EH, UK;
and Nordita, Blegdamsvej 17, DK-2100 Copenhagen Ø, Denmark; brandenb@nordita.dk
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through the convection zone. Here, however, we are envisaging the production of sunspots much closer to the surface, so the notion of flux tubes rising through a major portion of the convection zone is not invoked. Indeed, local helioseismology suggests a picture quite compatible with sunspots being a shallow surface phenomenon (Kosovichev et al. 2000, Kosovichev 2002). The actual sunspot formation might then be the result of convective collapse of magnetic fibrils (Zwaan 1978; Spruit & Zweibel 1979), possibly facilitated by negative turbulent magnetic pressure effects (Kleeorin et al. 1996) or by an instability (Kitchatinov & Mazur 2000) causing the vertical flux to concentrate into a tube.

Magnetohydrodynamic turbulence in the solar convective zone as a source of oscillations and sunspots formation

N. Kleeorin[1], **M. Mond**[1], **and I. Rogachevskii**[2]

[1] Department of Mechanical Engineering, Ben-Gurion University of Negev, POB 653, 84105 Beer-Sheva, Israel
[2] The Racah Institute of Physics, The Hebrew University of Jerusalem, 91904 Jerusalem, Israel

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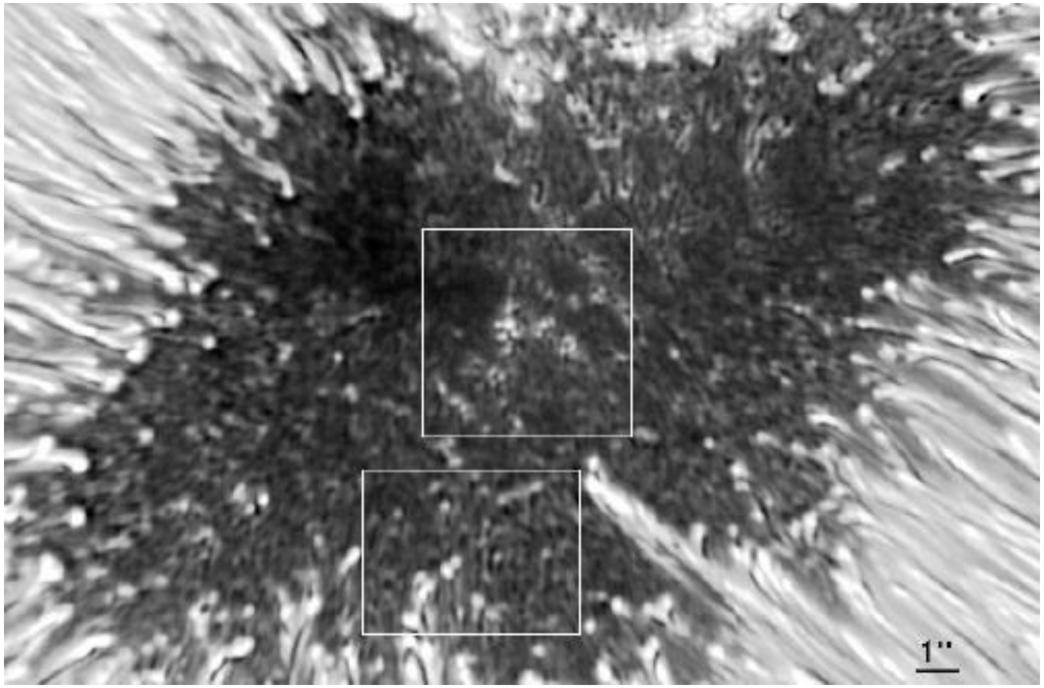
The MHD instability due to '*effective*' negative magnetic pressure in the interval $\kappa < \kappa_0$ may also provide a mechanism of the large-scale magnetic ropes formation in the solar convective zone (see also Kleeorin et al. 1989, 1990; Kleeorin & Rogachevskii 1990). At a depth $\sim 10^9$cm (from the sun's surface) the magnetic coefficient $Q_p \sim -1.8$ and the '*effective*' magnetic pressure is negative. The magnetic instability develops on a time scale $\tau_0 \sim 2.5 \cdot 10^5 s$. It apparently determines the formation of the magnetic flux tubes in the solar convective zone. These magnetic ropes float up from under the sun's surface leading to the onset of the observed sunspots.

Need for mean-field treatment

- Sunspot umbra turbulent, → scale separation
- Dynamos: Laminar picture not possible
  - Would be slow (large Rm)



Counter-intuitive turbulence

Theories of the solar cycle : a critical view

H.C. Spruit*
Max Planck Institute for Astrophysics
Box 1317, 85741 Garching, Germany

This striking behavior is the opposite of diffusion. To force it into a diffusion picture, one would have to reverse the arrow of time. Instead of opposite polarities decaying by diffusing into each other, they segregate out from a mix. The MHD equations are completely symmetric with respect to the sign of the magnetic field, however. There are no flows (no matter how complex) that can separate fields of different signs out of a mixture. This rules out a priori all models attempting to explain the formation of sunspots and active regions by turbulent diffusion. For recent such attempts, which actually ignore the observations they are trying to explain, see Kitiashvili et al. (2010), Brandenburg et al. (2010). The observations, instead, demonstrate that the orientation and location of the polarities seen in an active region must already be have been present in the initial conditions: in the layers below the surface from which the magnetic field traveled to the surface.

ON THE TURBULENT DECAY OF STRONG MAGNETIC FIELDS AND THE DEVELOPMENT OF SUNSPOT AREAS

F. KRAUSE and G. RÜDIGER

Zentralinstitut für Astrophysik der Akademie der Wissenschaften der D.D.R., Potsdam, D.D.R.

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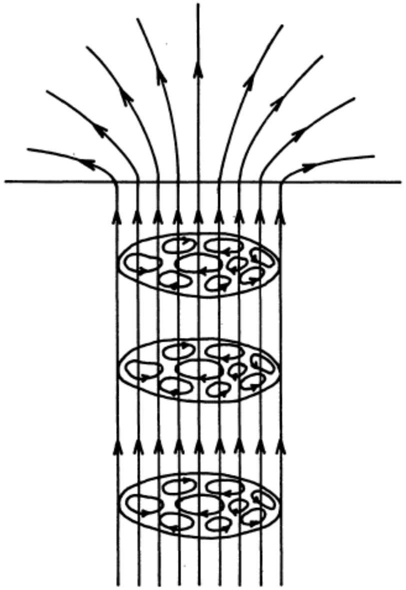
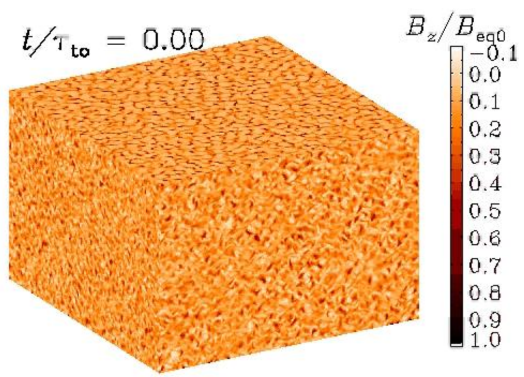
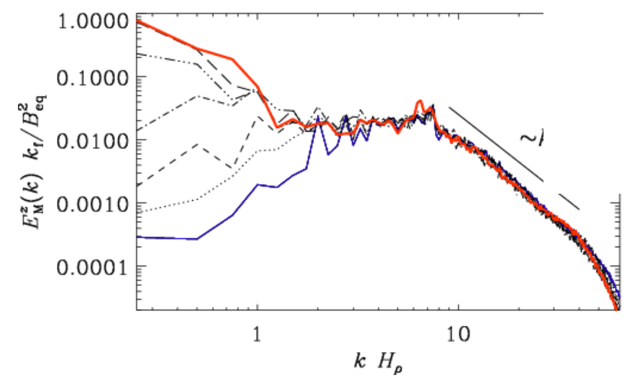
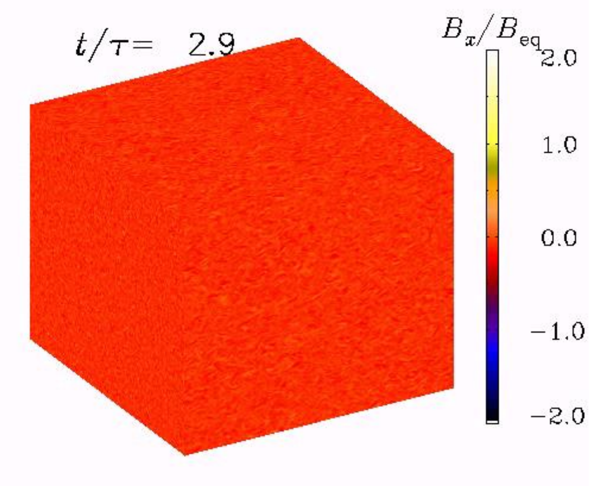
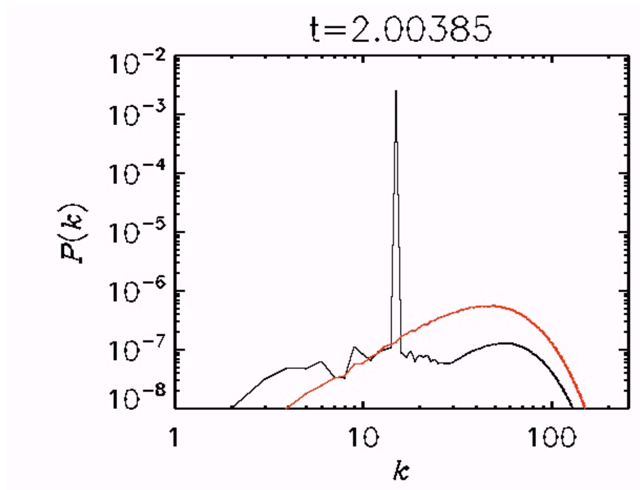






g.B → u.B



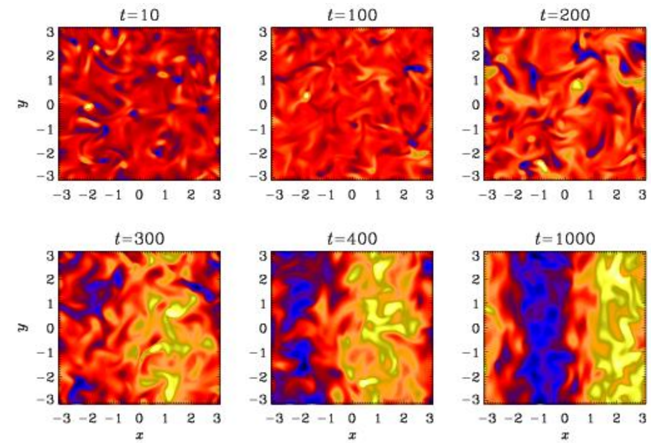


g.Ω
→ u.ω
→ A.B

Analogy: dynamo → spot mean-field modeling

dynamo

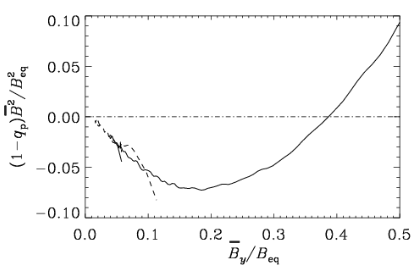
$$\overline{\mathbf{u}\times\mathbf{b}} = \alpha\overline{\mathbf{B}} - \eta_{\mathrm{t}}\overline{\mathbf{J}} + \ldots + \Xi\overline{\mathbf{U}} + \gamma\overline{\mathbf{W}}$$

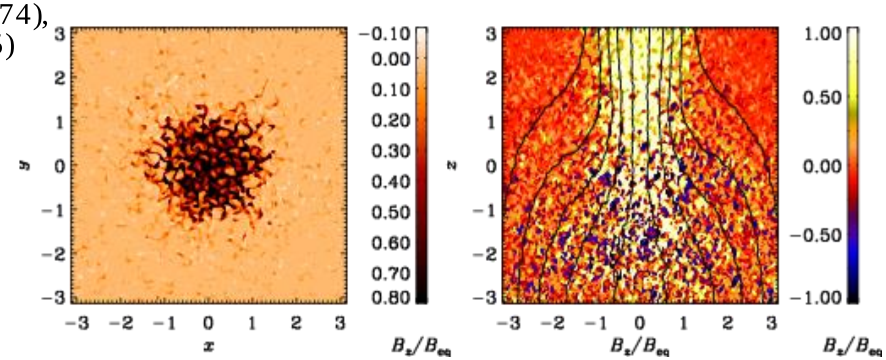


NEMPI

$$\overline{u_i u_j} = \Lambda_{ijk}\overline{\Omega}_k + \lambda_{ijk}\overline{U}_k + \ldots - \nu_{\mathrm{t}}\left(\overline{U}_{i,j} + \overline{U}_{j,i}\right) +$$

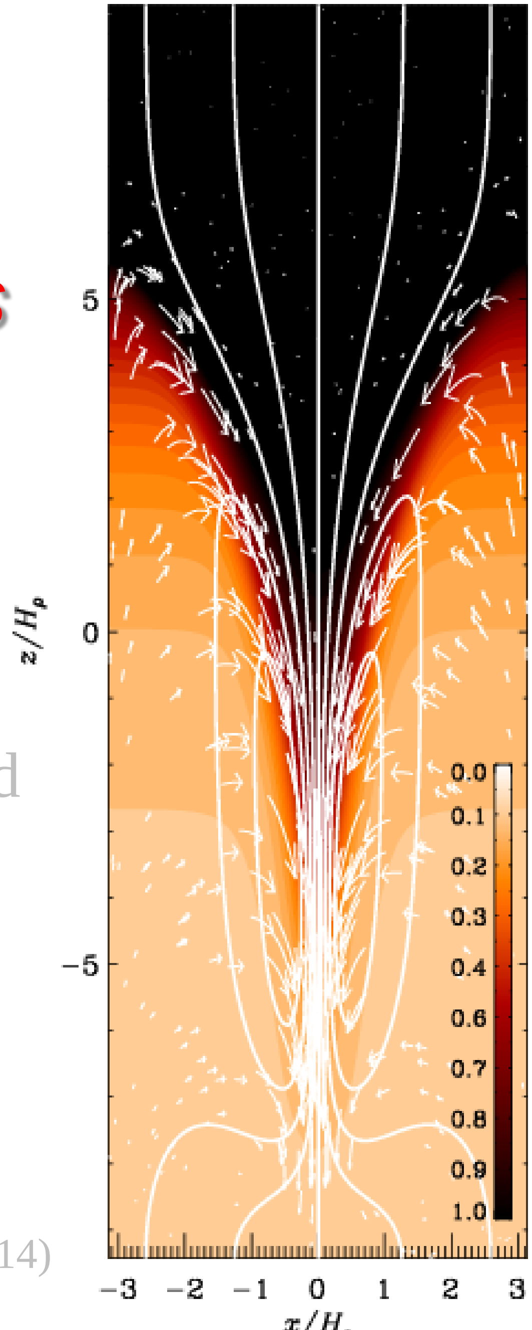
$$\ldots + \underbrace{\psi_{ijk}\overline{B}_k + \phi_{ijkl}\overline{B}_{k,l}}_{\text{Rheinhardt \& Brandenbug (2010)}} + \ldots + \underbrace{q_{\mathrm{s}}\overline{B}_i\overline{B}_j - \tfrac{1}{2}\delta_{ij}q_{\mathrm{p}}\overline{\mathbf{B}}^2}_{\text{Rädler (1974), Rüdiger (1974), Roberts \& Soward (1975)}} + \ldots$$

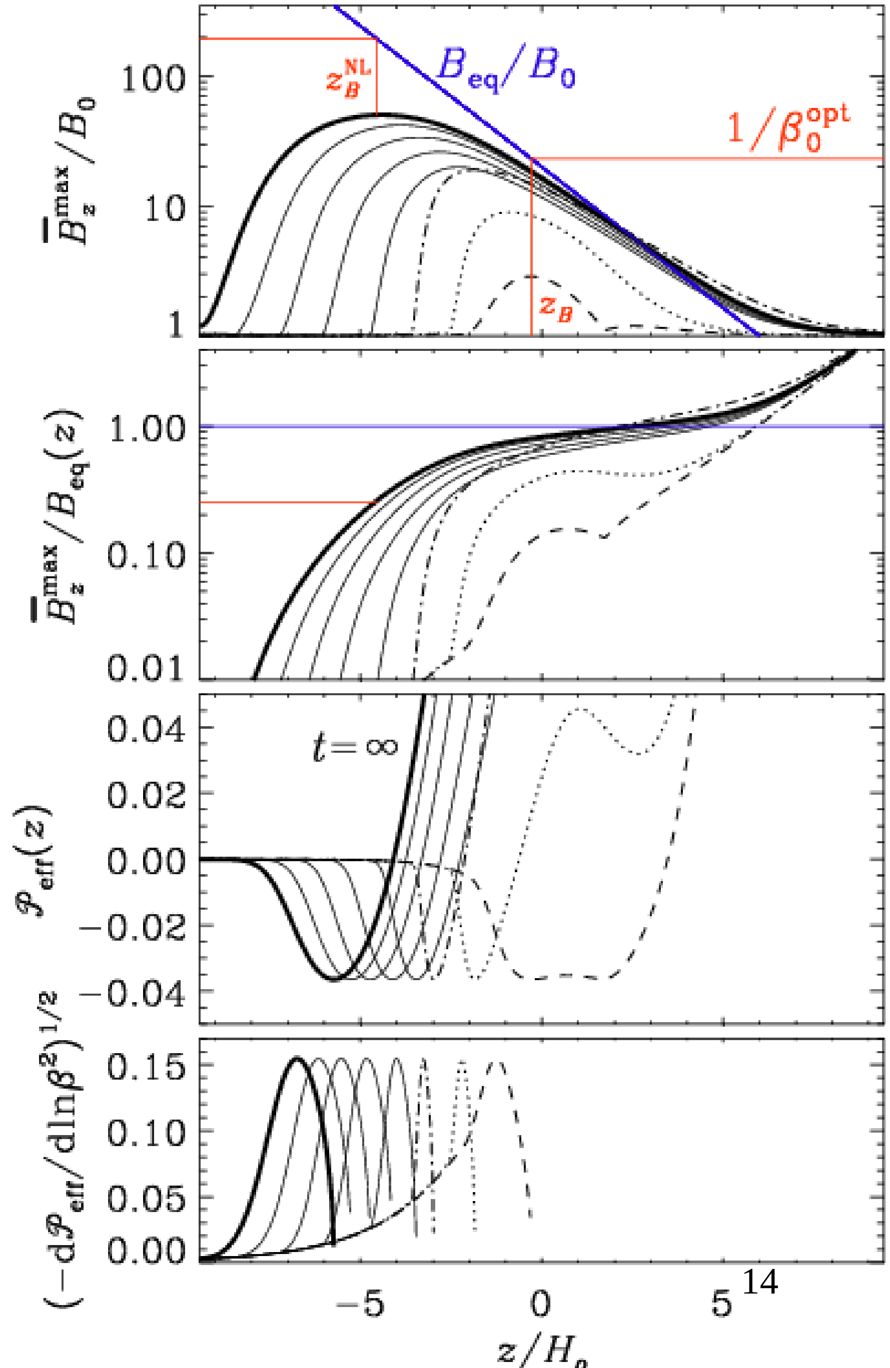




Sunspot formation that sucks

Mean-field simulation: Neg pressure parameterized



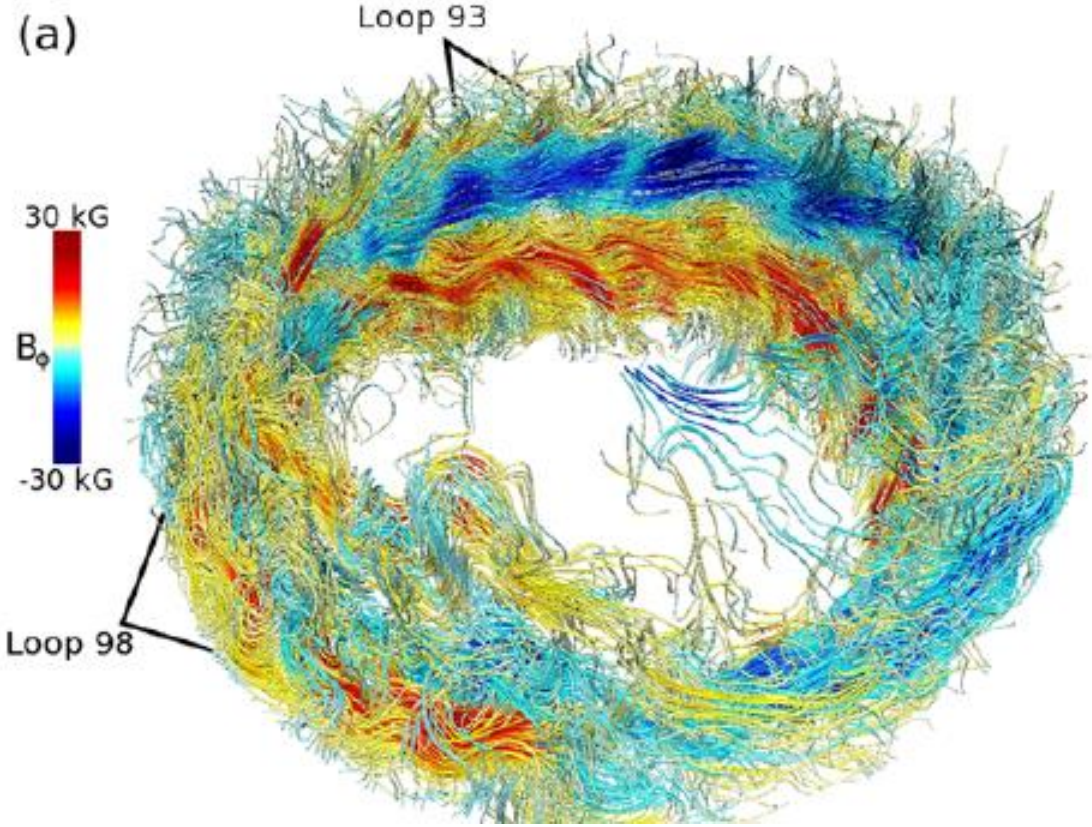


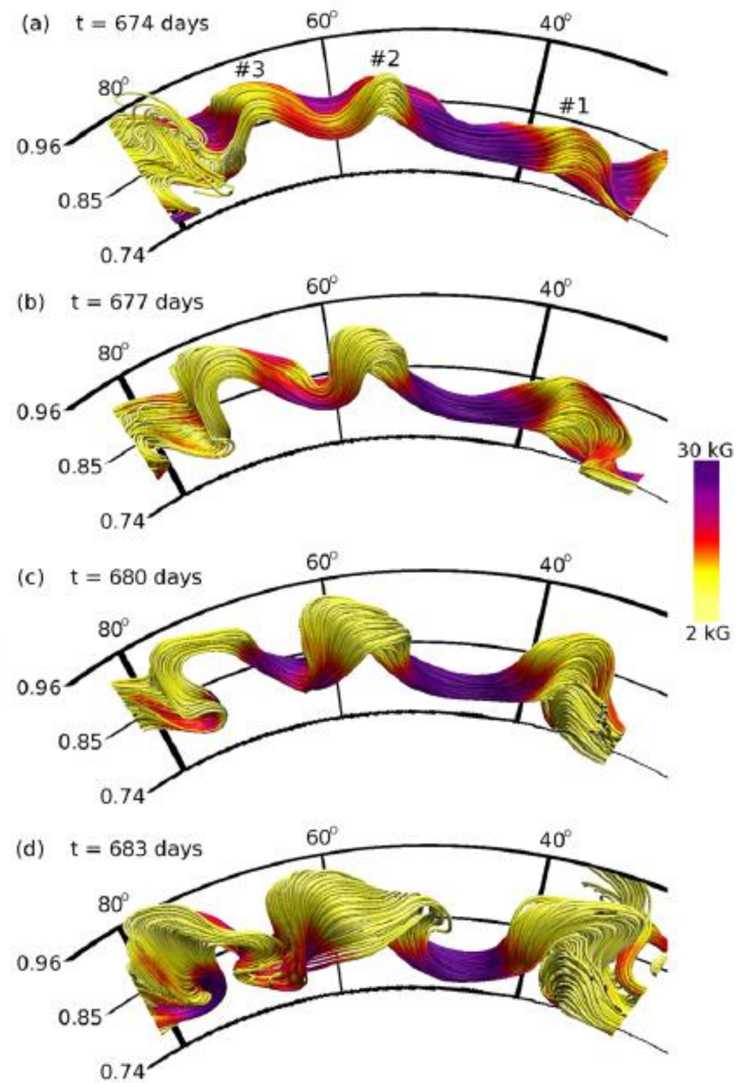
Typical downflow speeds Ma=0.2…0.3

Brandenbur et al (2014)

Flux tubes in global simulations

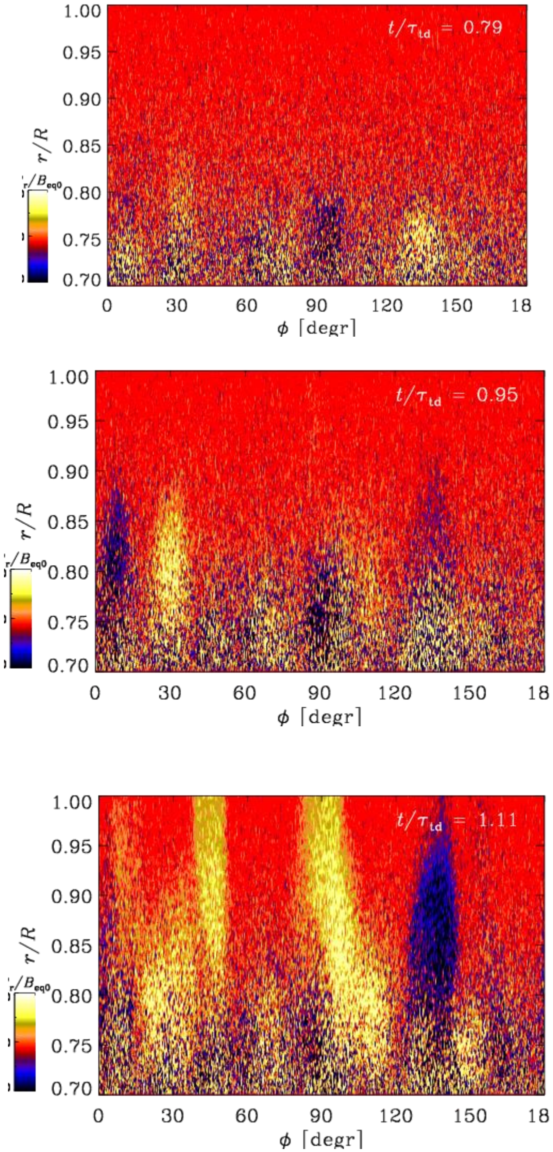
Nelson, Brown, Brun, Miesch, Toomre (2014)

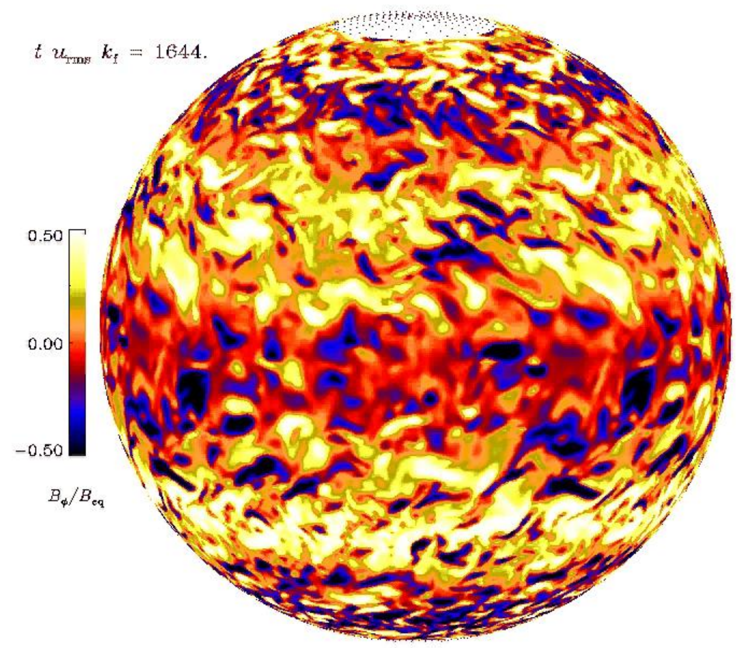




Synthesis

- Something else than NEMPI?
- Need mean-field description
- Connect with conv. dynamo

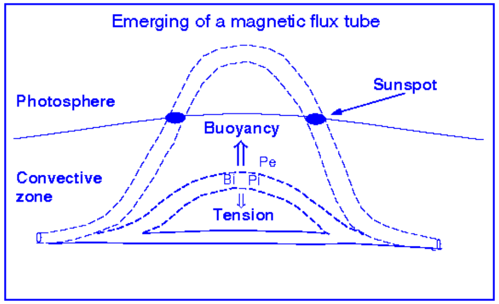




Jabbari et al. (2015)

AR & sunspots

- Rising flux tubes?
- Hierachical convection?
- Self-organization as part of the dynamo
- Can we ever distinguish?



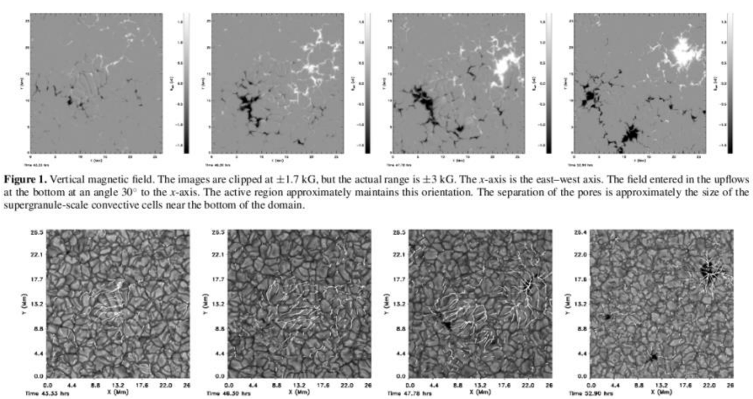
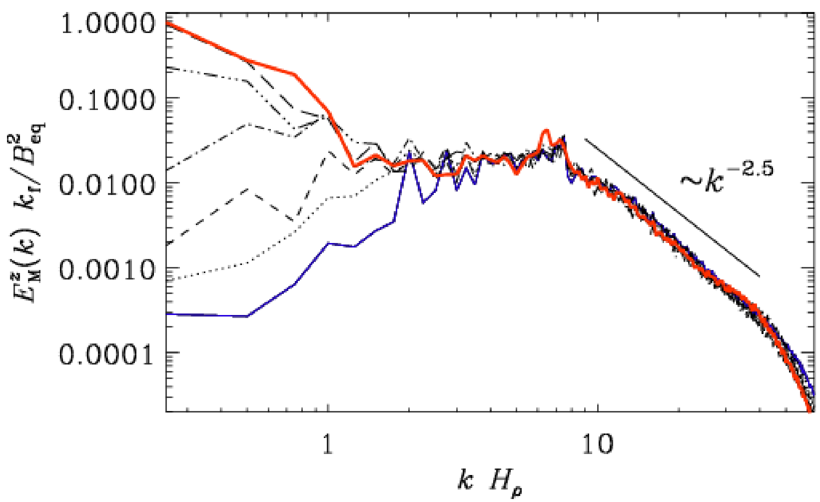
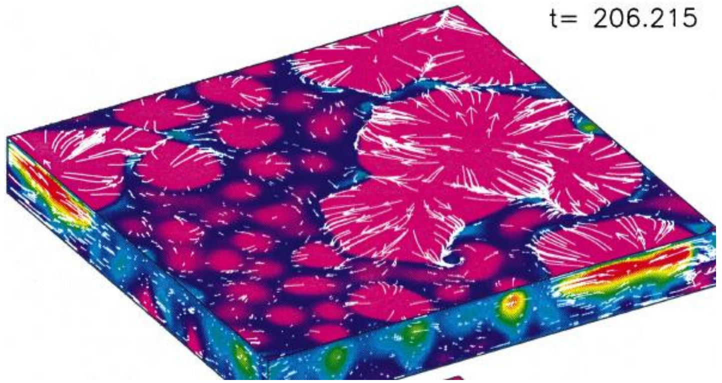

THE ASTROPHYSICAL JOURNAL LETTERS, 753:L13 (2pp), 2012 July 1
STEIN & NORDLUND

Figure 1. Vertical magnetic field. The images are clipped at ±1.7 kG, but the actual range is ±3 kG. The x-axis is the east–west axis. The field entered in the upflows at the bottom at an angle 30° to the x-axis. The active region approximately maintains this orientation. The separation of the pores is approximately the size of the supergranule-scale convective cells near the bottom of the domain.

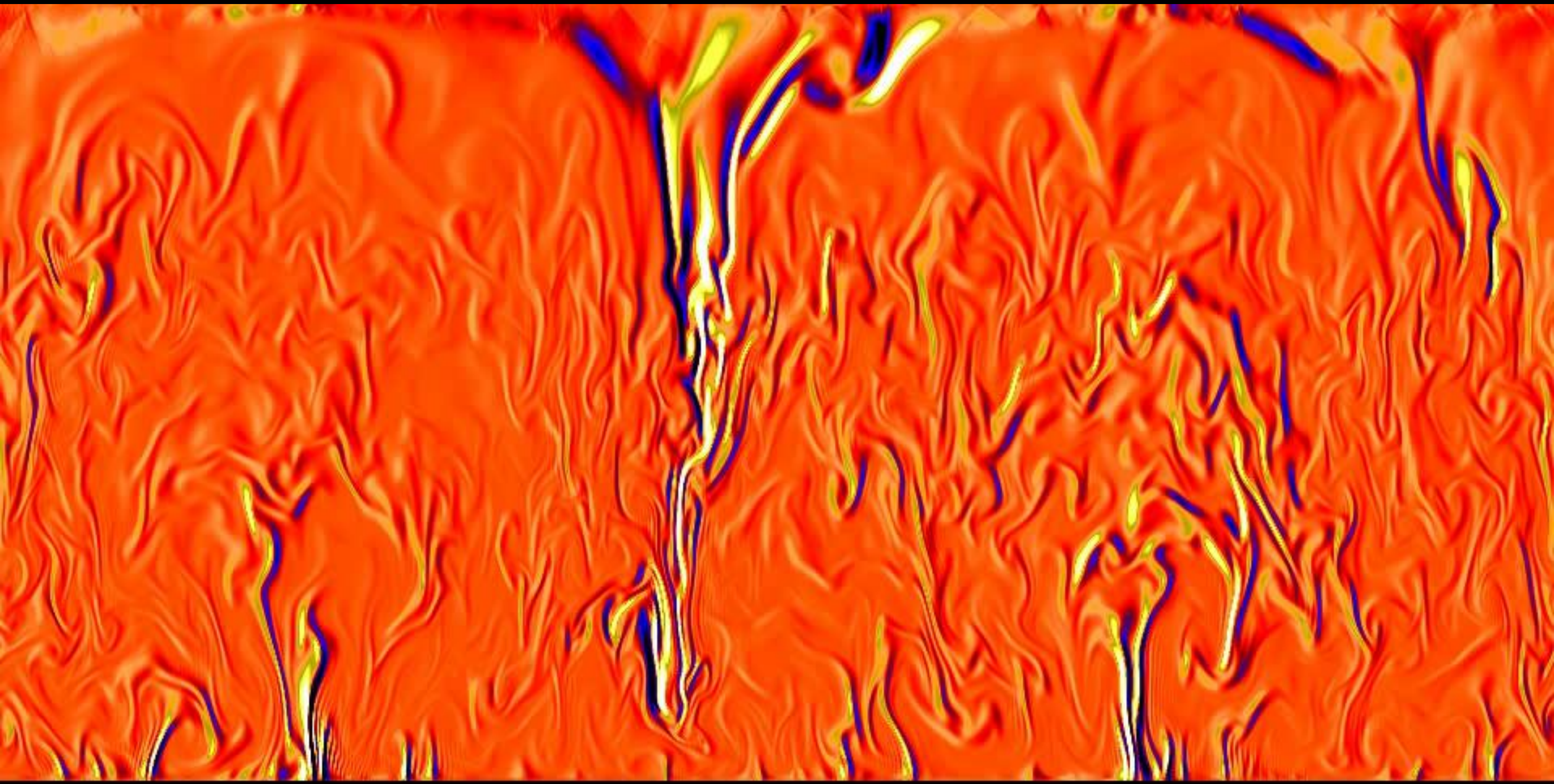
Figure 2. Continuum intensity image with horizontal magnetic field vectors superimposed. The images are clipped at $2.3 > I/\langle I \rangle > 0.5$. The actual range is [0.2, 2.5]. In the initial emergence the granules are elongated transverse to the horizontal field. Thereafter the granules appear elongated along the magnetic field direction.





Tao et al (1998)

Isothermal NEMP convection



Losada et al. (in prep)

Conclusions

- Downflows ←→ spot formation
- Mean-field description
- Predictive model
- Analogy with dynamo
- Really NEMPI or

  yet something else?