Unification of Babcock-Leighton Dynamo models with Surface Flux Transport Models

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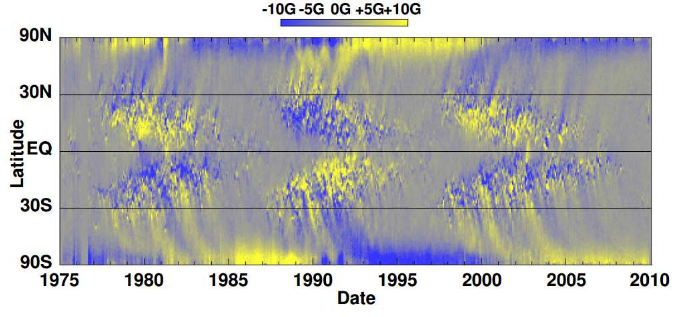
Photospheric Magnetic Field

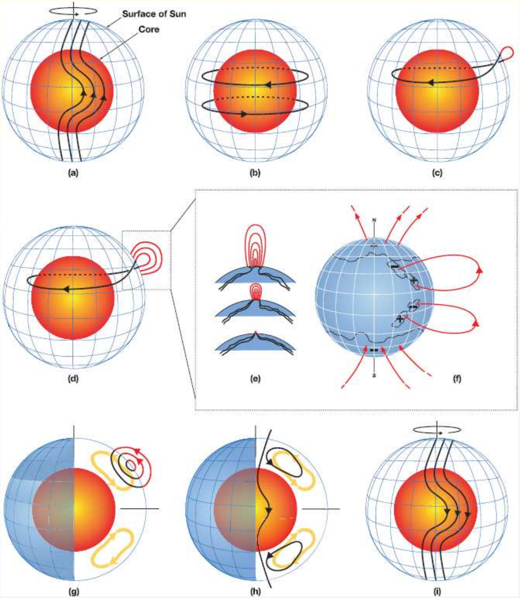
Importance of studying evolution of large scale surface magnetic field:

- Sets the structure of the heliospheric magnetic field
- Only observable part of the Babcock-Leighton Dynamo



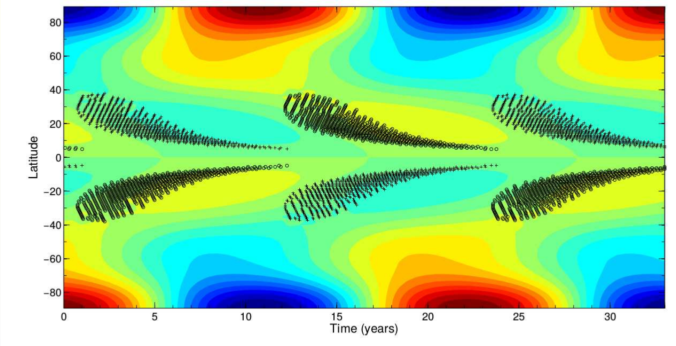
[Hathaway et. al (2010)]

Babcock-Leighton Dynamo Models



Babcock-Leighton Dynamo Models

a.k.a Flux Transport Dynamo Model (Axisymmetric Model!!)



[Thesis (2012), B B karak]

- Successfully model the 11-year solar cycle and its irregularities
- Structure of the surface magnetic field is not captured.

Surface Flux Transport Models

Solves induction equation on the surface of the sun with $v_r = 0$ & $\frac{\partial}{\partial r} = 0$

$$\frac{\partial B_r}{\partial t} = \frac{1}{sin\theta}\frac{\partial}{\partial\theta}\left[sin\theta\left(-u(\theta)B_r + D\frac{\partial B_r}{\partial\theta}\right)\right] - \Omega(\theta)\frac{\partial B_r}{\partial\phi} + \frac{D}{sin^2\theta}\frac{\partial^2 B_r}{\partial\phi^2} + S(\theta,\phi,t)$$

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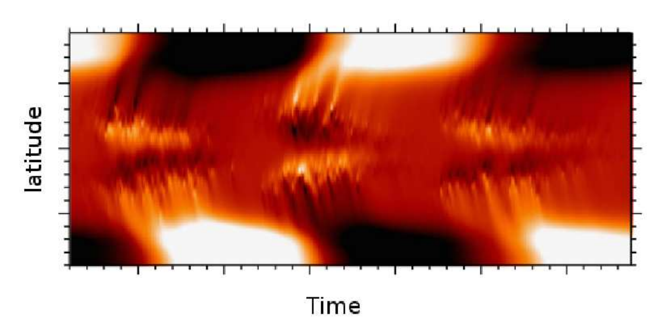


[Jiang et al. (2010)]

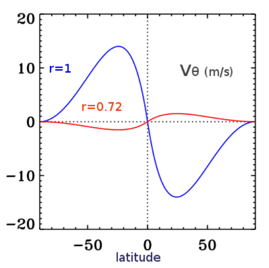
Simulates the surface magnetic field quite well!

Develop a model which will simulate the surface magnetic field from the dynamo generated field self consistently and captures the 11 year solar cycle.

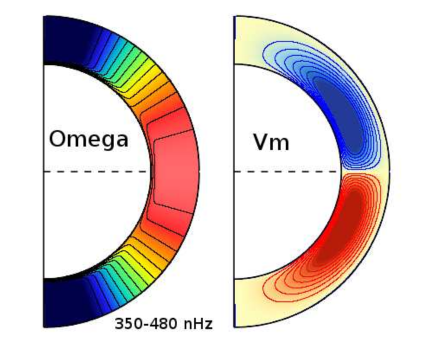
Unified 3D Babcock-Leighton Model

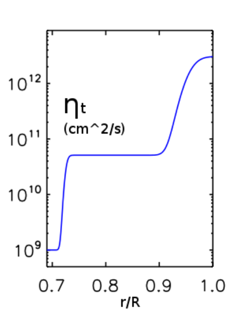
Solve 3D kinematic induction equation
(Non-Axisymmetric !!!)

$$\frac{\partial B}{\partial t} = \nabla \times (v \times B - \eta_t \nabla \times B)$$



[Dikpati et al (2010, 2011)]





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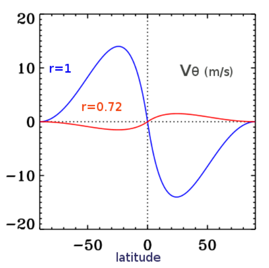

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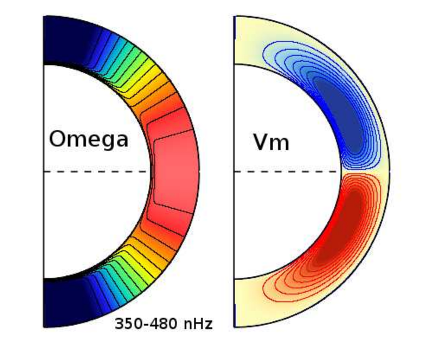

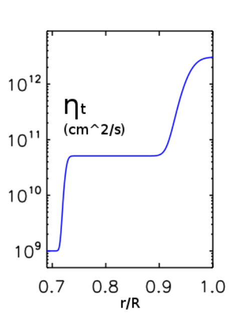

Spot Making Algorithm

- Introduce spots sporadically and systematically, based on dynamo generated field.
- Let them evolve naturally, under the influence of mean flows and η_t

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Where ?

Spot producing field:

$$B_\phi(\theta.\phi, t) = \int_{r_a}^{r_b} h(r) B_\phi(r, \theta, \phi) dr$$

where $h(r) = h_0(r - r_a)(r_b - r), r_a = 0.71 R_\odot, r_b = 0.70 R_\odot$

if $B^*(\theta, \phi, t) = g(\theta)|B_\phi(\theta, \phi, t)| > B_t$ **place spots on the surface**

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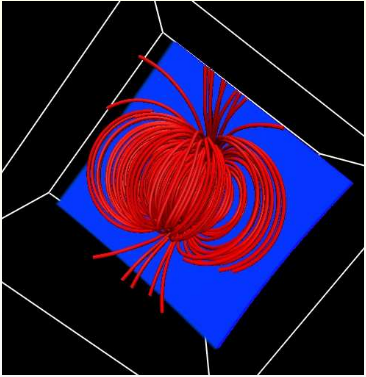
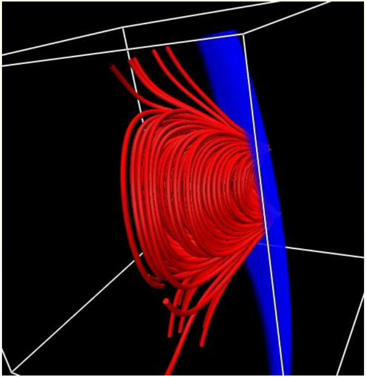
When ?

Introduced some time delay and randomness!!

[Miesch & Dikpati (2014)]

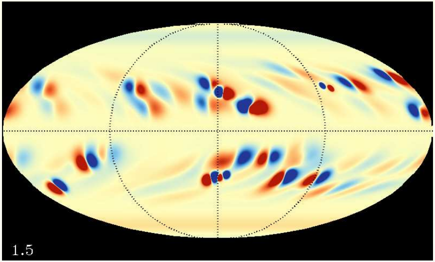
Bipolar Spots are localized to the surface layers only.





Spots quickly decouple from deep roots [Longcope & Choudhuri 2002, Schüssler & Rempel 2005]

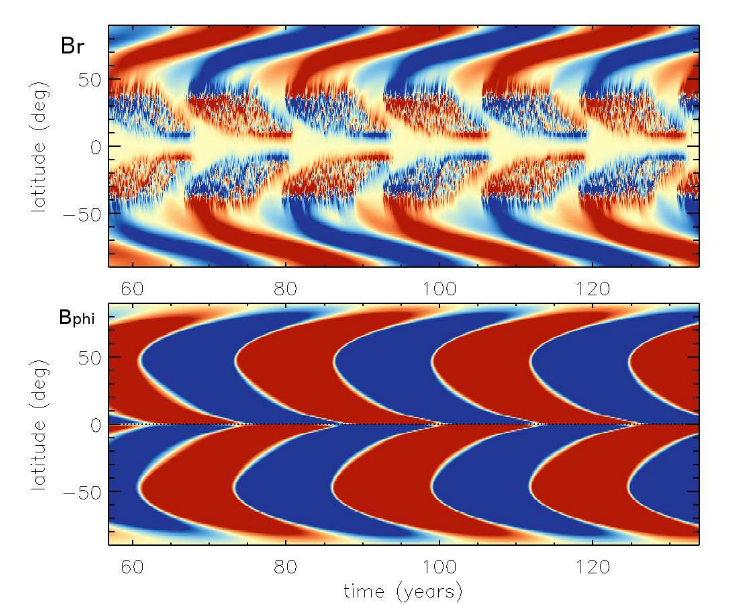
Results: sunspots



Self sustained 3D dynamo model which has sunspots and sunspots play very essential role in operation of dynamo

This is not the first. See *Yeats & Muñoz − Jaramillo, A.*(2013).

Butterfly Diagrams



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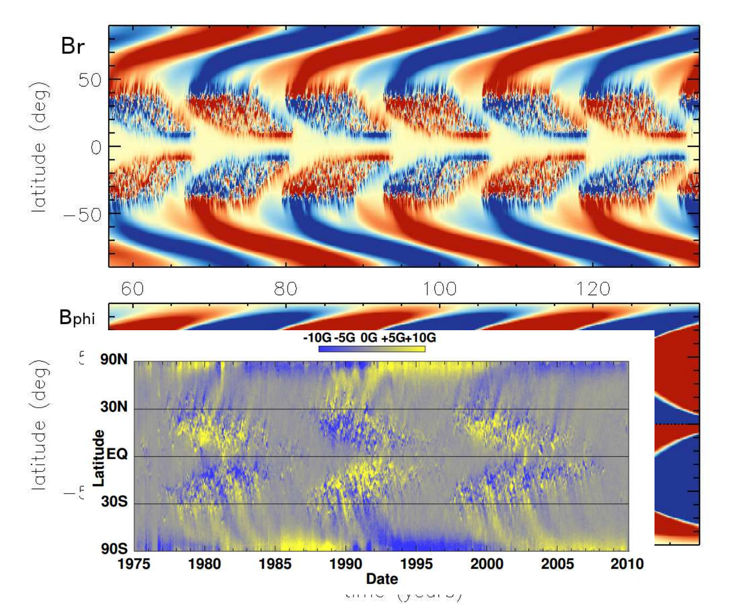
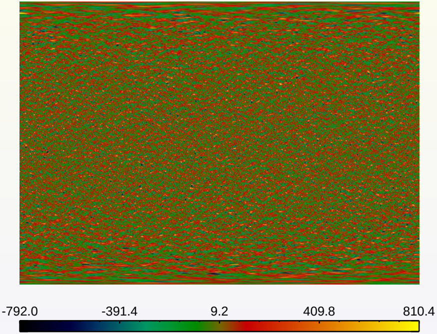
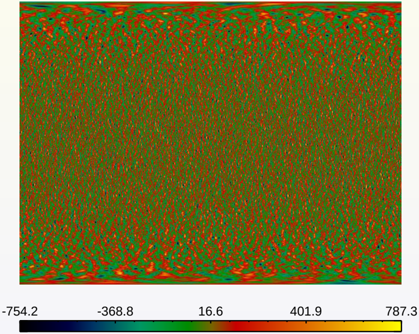


Convective flow fields

Simulated flow fields ($V_\theta \& V_\phi$) from Doppler Velocity data (SDO)





[Upton & Hathaway, 2014a,b]

Incorporating Data in Simulation

Assumption:

1. Mass flux is divergence less

$$\nabla . \rho \mathbf{v} = 0 \tag{1}$$

2. Convection in upper CZ is completely poloidal

$$\rho \mathbf{v} = \nabla \times \nabla \times W \hat{r} \tag{2}$$

Obtaining 3D Convective Flows:

From Observation we have measurement of horizontal flows (V_h)
Eqn(1) $\Rightarrow$

$$\nabla_h . (\rho V_h) = -\frac{1}{r^2} \frac{\partial}{\partial r} (r^2 \rho V_r) = -\frac{l(l+1)}{r^2} \frac{\partial W}{\partial r} \tag{3}$$

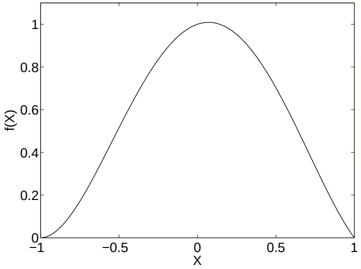
Now since $W(r, \theta, \phi) = f(r) g(\theta, \phi)$ so Eqn(3) $\Rightarrow$ $g(\theta, \phi) = \frac{r^2 \nabla_h . (\rho V_h)}{l(l+1) \frac{\partial F}{\partial r}}$

Extrapolation downward:

So we need $F(r)$ and $\frac{\partial F}{\partial r}$

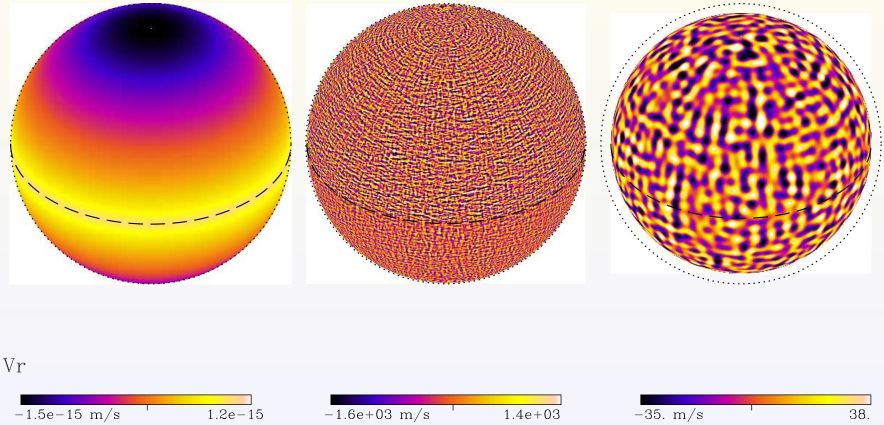
- $f(x) = a + bx + cx^2 + dx^3 + ex^4$,
  where $x = \frac{r - r_w}{r - r_p}$

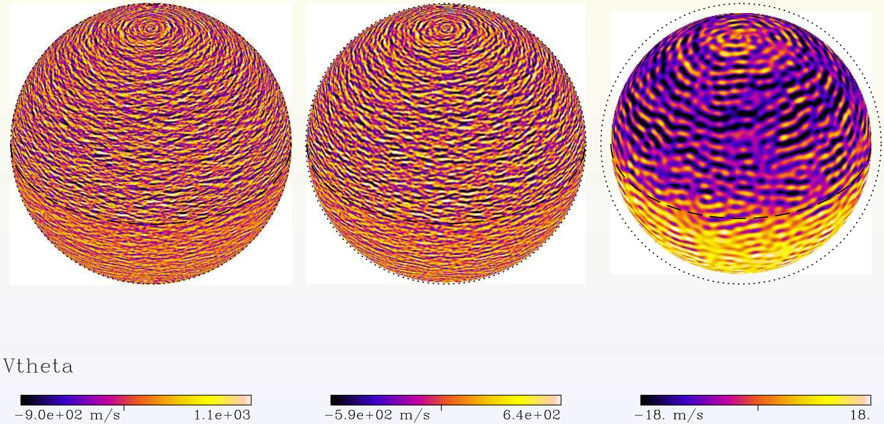
- Have chosen $f(r)$ so that
  $f(r) = 0, r = R_\odot$ & $r = r_p$ and
  $f(r) = 1, r = r_w$
  where, $r_w = R_\odot(1 - \pi/l)$ and
  $r_p = R_\odot(1 - 2\pi/l)$

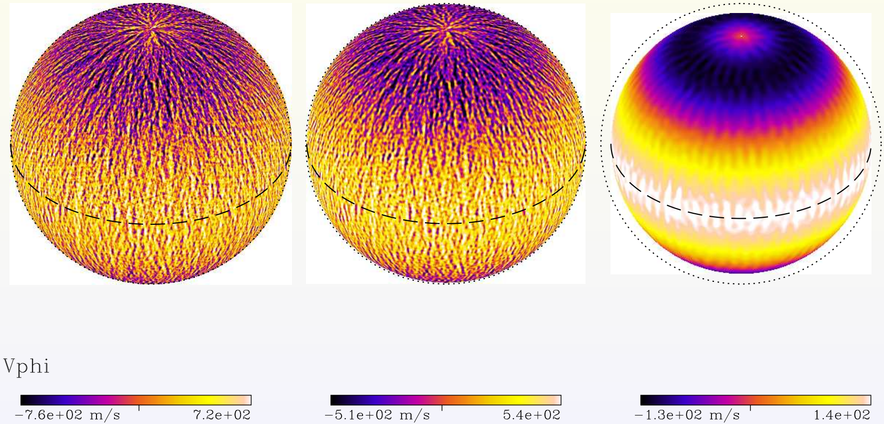


Hence we can calulate $W(r, \theta, \phi) = f(r)g(\theta, \phi)$ and then all three velocity component

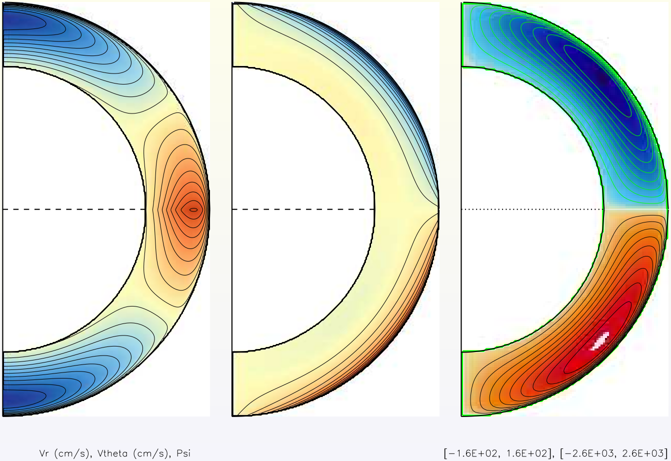
Extrapolated Convective velocity fields




Vtheta
−9.0e+02 m/s
1.1e+03
−5.9e+02 m/s
6.4e+02
−18. m/s
18.

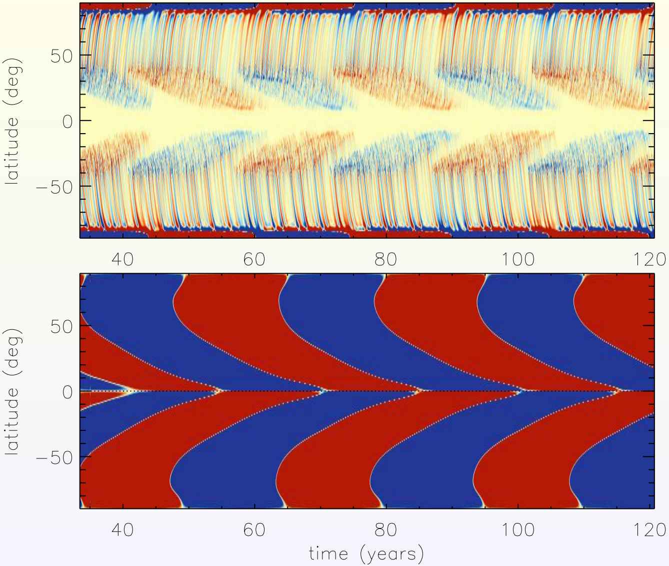

Vphi
−7.6e+02 m/s
7.2e+02
−5.1e+02 m/s
5.4e+02
−1.3e+02 m/s
1.4e+02

Axisymmetric flow



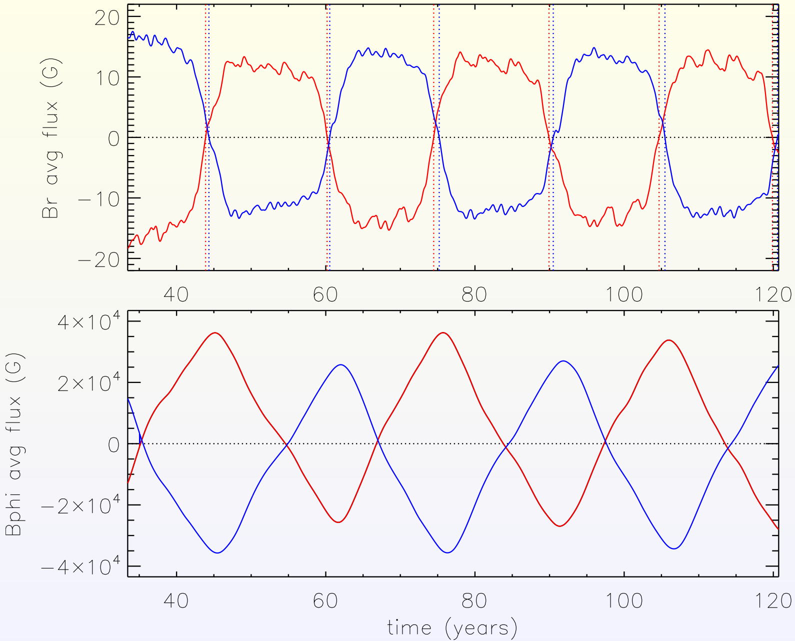
[Chatterjee et al. 2004]

Simulated magnetic field



[Hazra & Miesch (2015) in Prep.]

Poloidal Fields and Toroidal Fields



Summary

- Spot algorithm is used for better treatment of surface flux transport.
- Realistic convective flow from observation is incorporated in simulation.
- Evolution of photospheric magnetic field is captured well.
- Unification of this two model is already done but in future we want to incorporate time varying flow fields from observation also