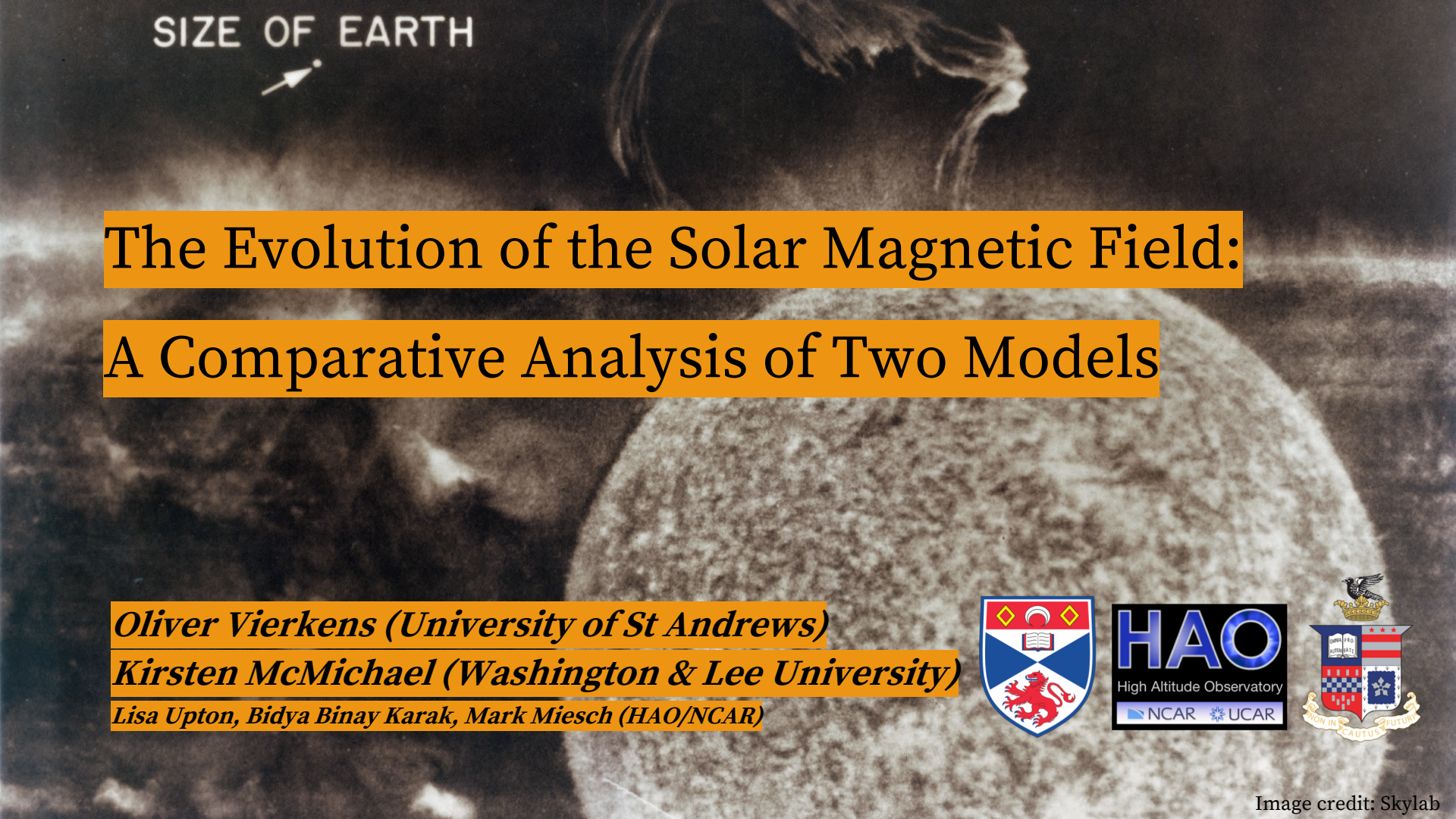

The Evolution of the Solar Magnetic Field: A Comparative Analysis of Two Models

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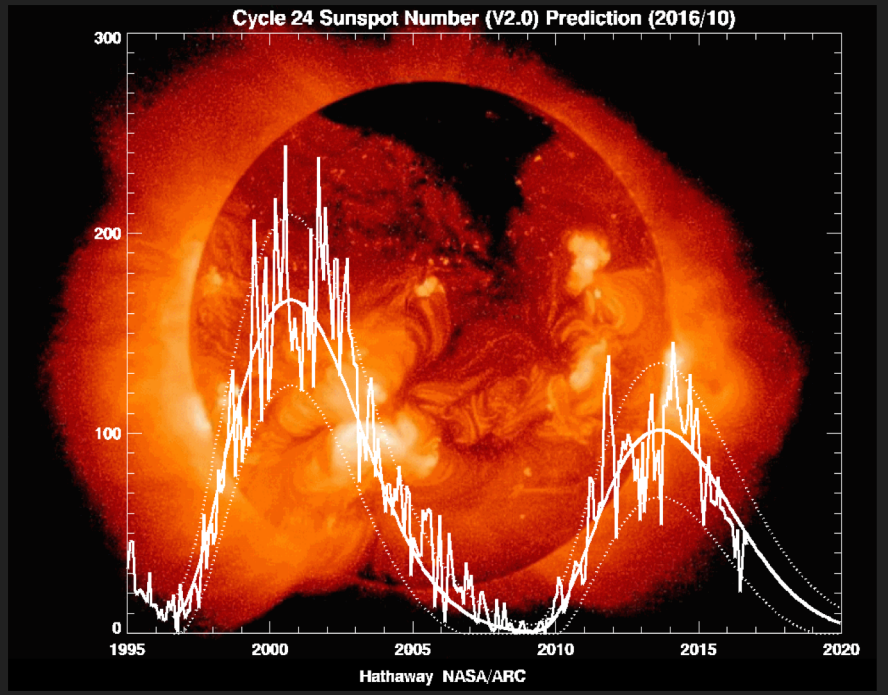
Image credit: Skylab

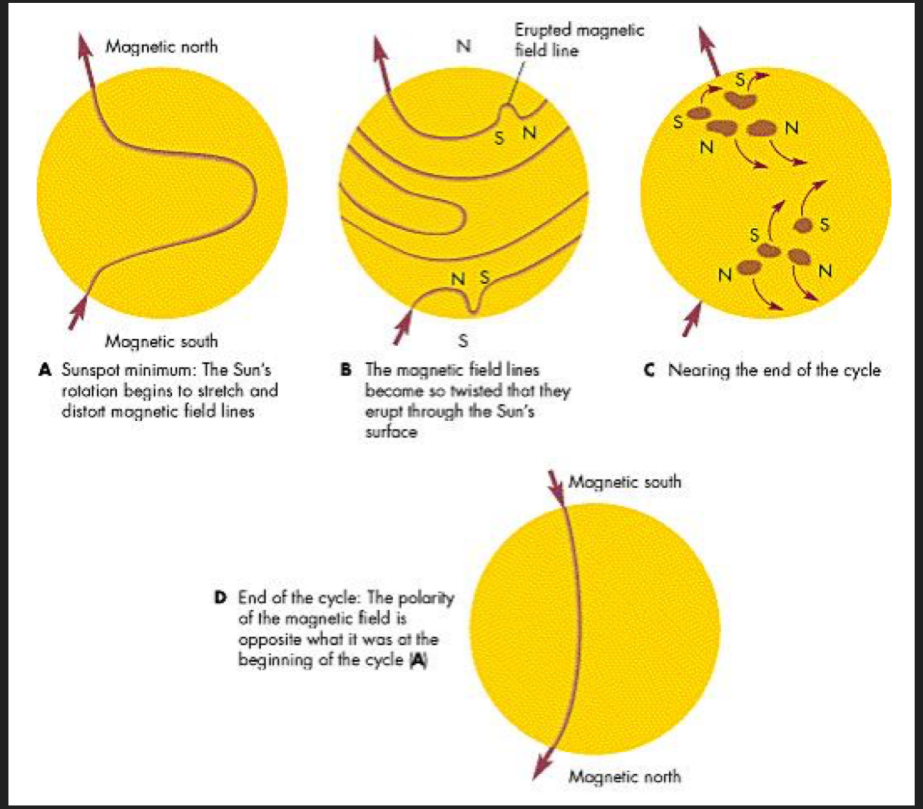
Overview

- Big challenge: understanding the 11-year solar activity cycle
- Simply put: understanding the evolution of the Sun's magnetic field…
- … since most solar phenomena are magnetic in nature (CME's, sunspots, etc.)
- Important consequences for life on Earth (and in space!)



Overview

- Widely accepted “high level” model: Babcock-Leighton
- Simulations essentially model how magnetic elements get transported in accordance with various flows on the Sun
- Two different models in the works: 2D surface flux transport model & 3D dynamo model (AFT and STABLE).
- Our question: can we combine the successes of both models?



McGraw-Hill:
http://www.mhhe.com/physsci/astronomy/fix/student/chapter17/17f37.html

Advective Flux Transport (AFT)

From MHD theory we have the induction equation:

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

- Small diffusivity
- B is entirely radial

$$\frac{\partial B_r}{\partial t} = (\nabla \times (v \times B))_r$$

2D advection!

- This is the fundamental equation describing the time evolution of the magnetic field in a plasma
- From solar observations we can make certain simplifications when applying the equation to the surface only

Advective Flux Transport (AFT)

$$\frac{\partial B_r}{\partial t} = (\nabla \times (v \times B))_r$$

- So it all reduces down to a purely advective equation on a spherical shell
- Advection - think of B- field as scalars being transported by a velocity field
- The finesse of the model comes from designing a sensible surface velocity field (v)
- We have:
  - Differential rotation & meridional flow
  - Convection - unique to AFT

Why is AFT successful

- The plasma flows on surface of the Sun are well-understood. On the surface we have good knowledge about …
- … the differential rotation and meridional flow patterns
- … the molecular diffusivity (small)
- … convective cell patterns
- Dealing with the surface only → fewer free parameters
- All in all, AFT is great for incorporating observational data into simulations

Observation

AFT model

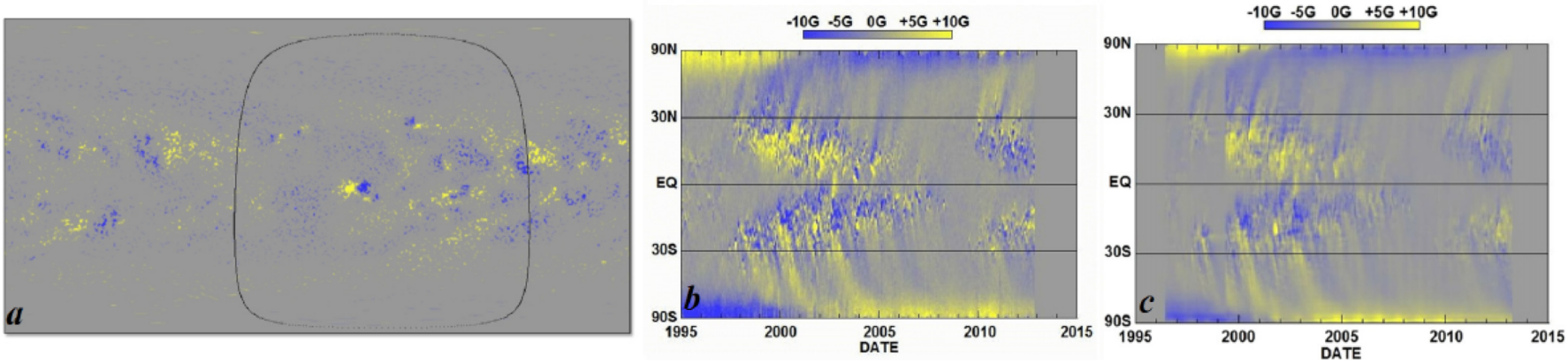


Fig 2: Illustrative results from the AFT SFT model (Upton & Hathaway 2014a,b). (*a*) Synchronic maps (latitude/longitude) produced by AFT show B_r at the solar surface, with black lines indicating the window where observational data from the SOHO/MDI instrument (Jan 1, 2001) is being assimilated. Magnetic butterfly diagrams (longitudinally-averaged B_r) constructed from (*b*) NSO/Kitt Peak observations and (*c*) AFT show excellent agreement.

A summary of AFT

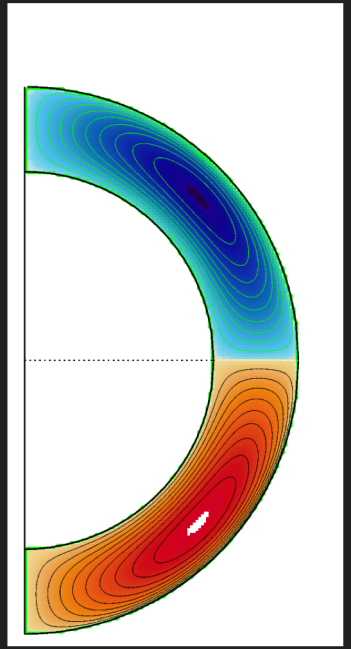
- Purely advective 2D model, where the radial magnetic flux is advected by a longitudinal and latitudinal velocity field.
- Magnetic elements are pushed around by simulated convective cells, differential rotation, and meridional flows on the **surface of the Sun only**.
- Since the flows on the surface of the Sun are more well-understood than in the deeper layers of the photosphere, AFT makes a good model for incorporating observational data into simulations.
- Successful at predicting polar field strengths 3-5 years in advance, given a history of active regions.

STABLE

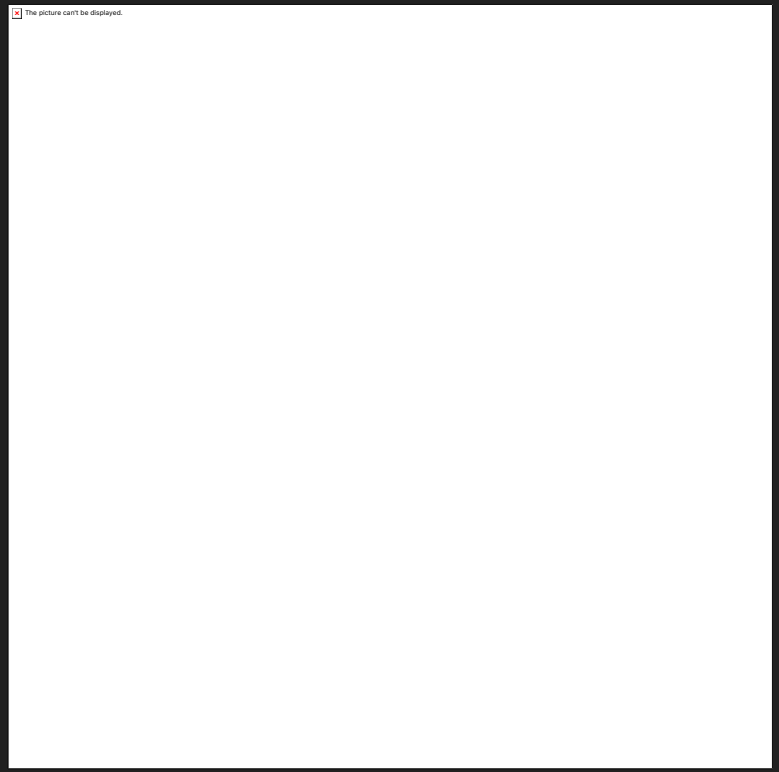
(Miesch & Dikpati 2014; Miesch & Teweldebirhan 2015)

- **S**urface **T**ransport **A**nd **B**abcock **LE**ighton Model
- 3D Dynamo Model of Sun
- Runs on a supercomputer
- Solves the induction equation in 3D spherical coordinates

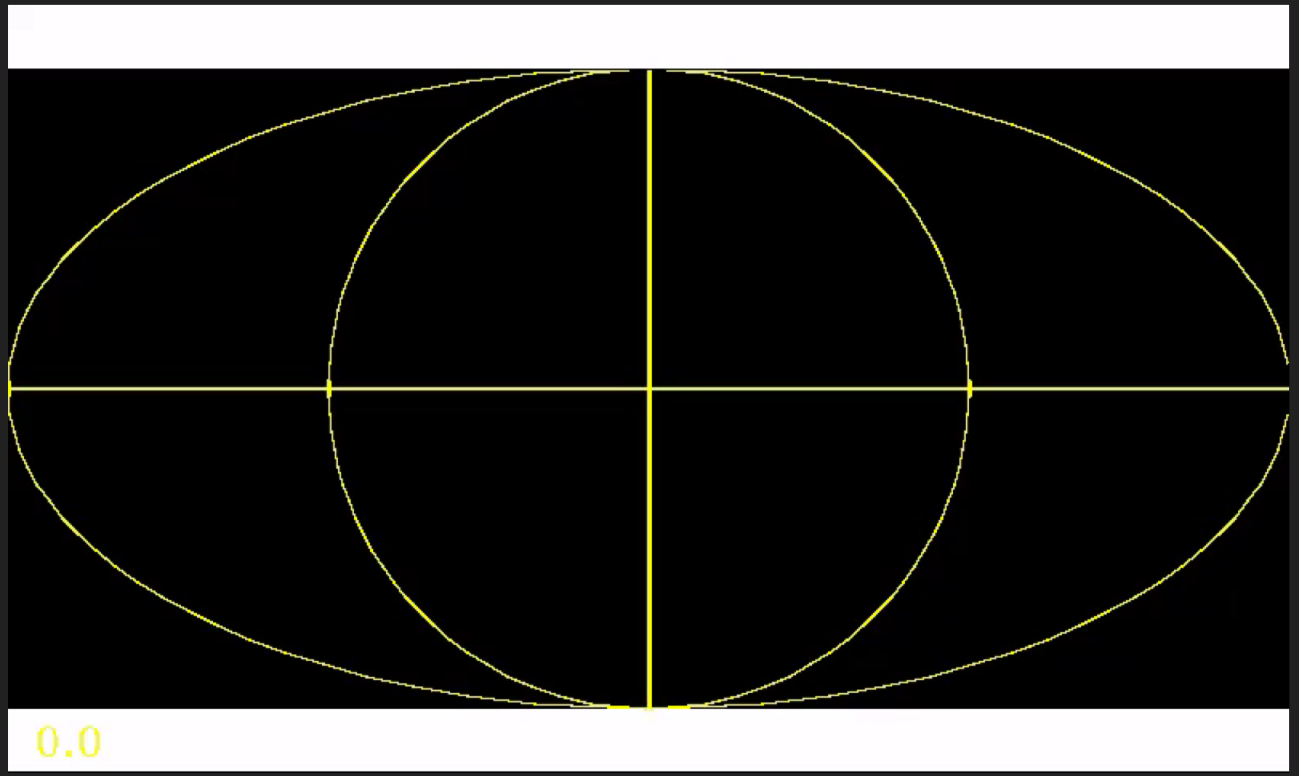
$$\frac{\partial \vec{B}}{\partial t} = \eta \nabla^2 \vec{B} + \vec{\nabla} \times (\vec{v} \times \vec{B}).$$



STABLE



STABLE



Diffusivity Values

The Induction Equation $\frac{\partial \vec{B}}{\partial t} = \eta \nabla^2 \vec{B} + \vec{\nabla} \times (\vec{v} \times \vec{B})$.

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

$$D = \eta \nabla_H^2 B_r + \eta \frac{\partial^2 B_r}{\partial r^2} + \eta \frac{2}{r}\frac{\partial B_r}{\partial r} - \eta \frac{2}{r^2} B_r$$

Tasks and Goals

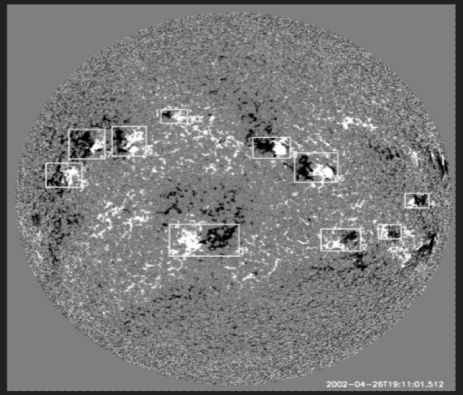
- Analyze evolution of the magnetic cycle
- Compare results between a surface transport model and a 3D dynamo model
- Develop a better understanding of solar cycles
- Increase precision and accuracy of both models by identifying differences

Reason for Comparison

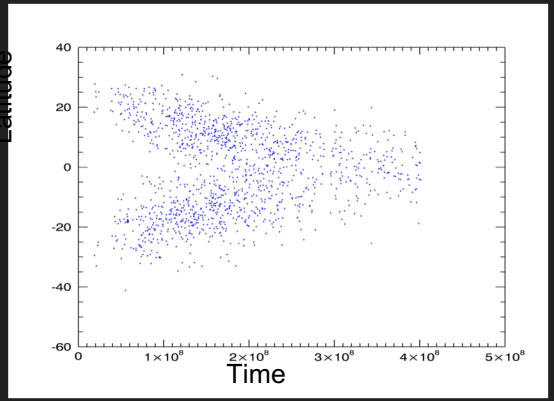
- Constrain free parameters in STABLE
- AFT has a proven capability of assimilating observational data
- Dynamo models have potential for making long term solar predictions

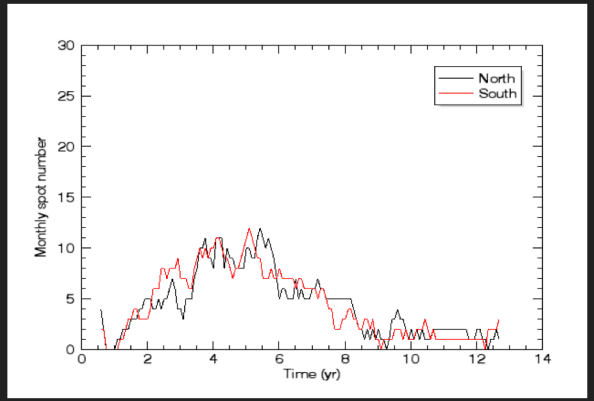
Model Input

- Insert synthetic sunspots into the model
  - Flux, Leading Latitude, Leading Longitude, Trailing Latitude, Trailing Longitude, Time
- Full cycle and single spot data
- STABLE reads in two separate files, one for each hemisphere



Stenflo & Kosovichev (2012)



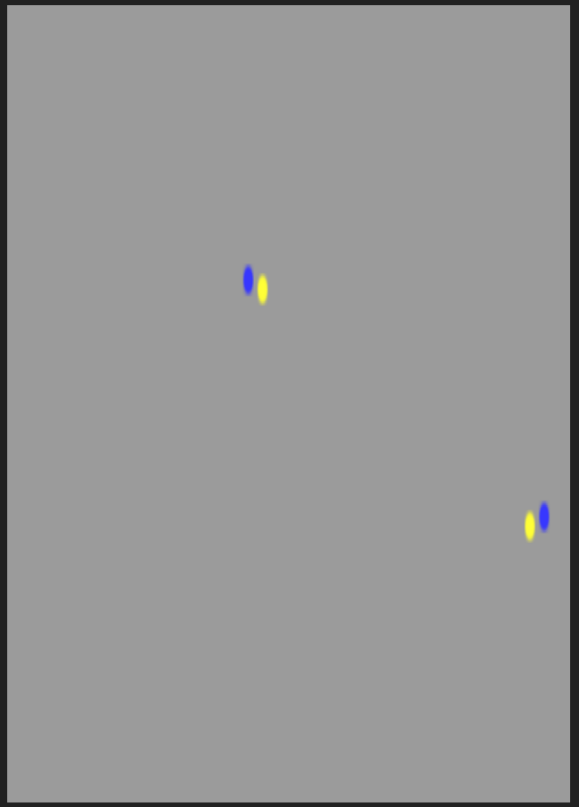


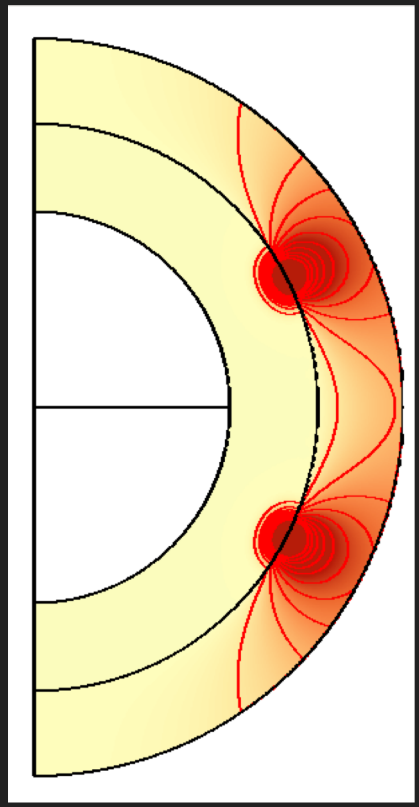
Similarities Between Models

- BMR input data
- Flow profiles
- Diffusivity (Eta)
- Boundary Conditions

Differences Between Models

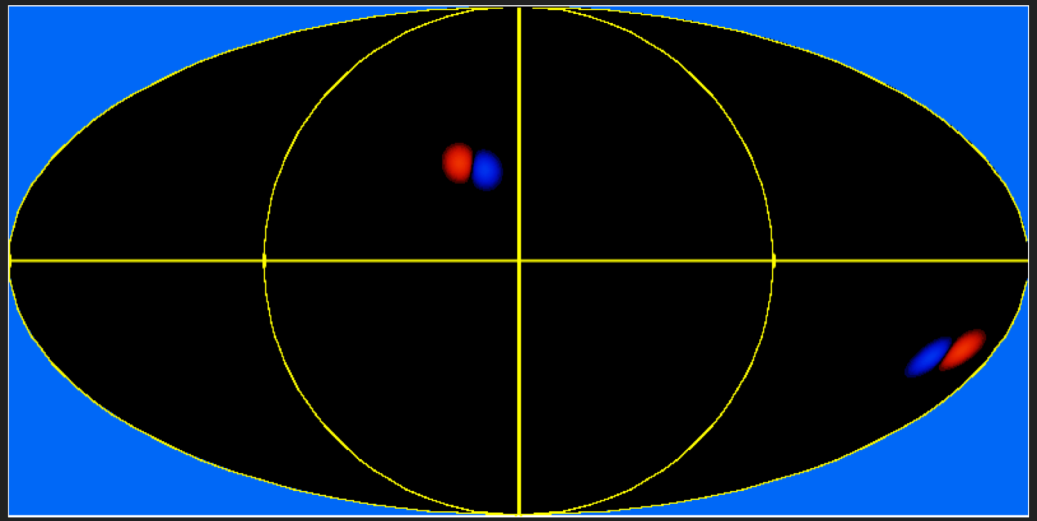
- Free parameters in STABLE
- Source term
  - Spot structure



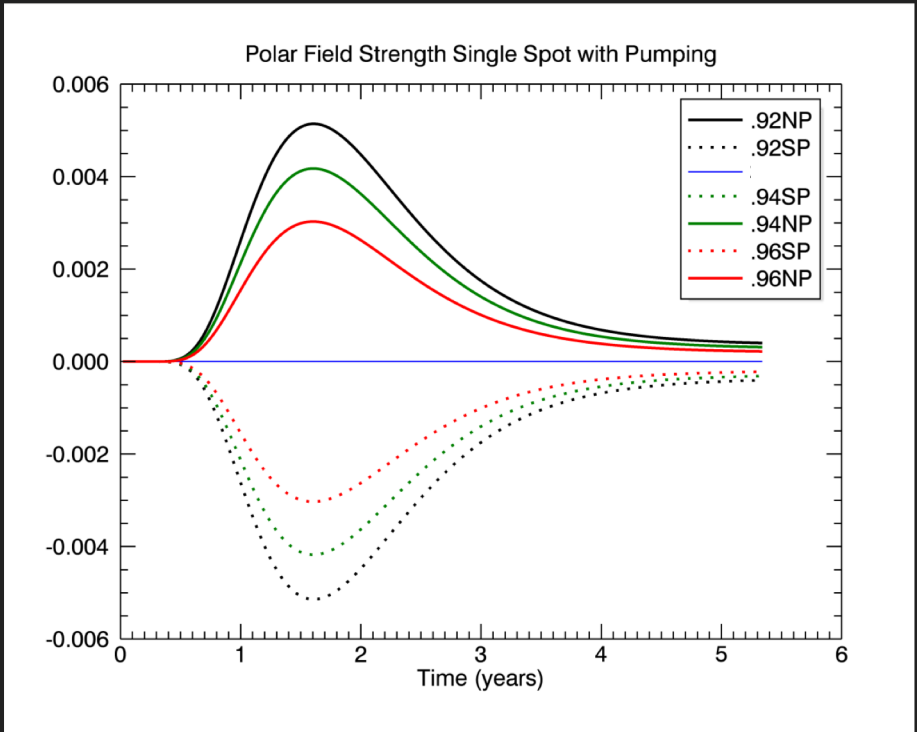


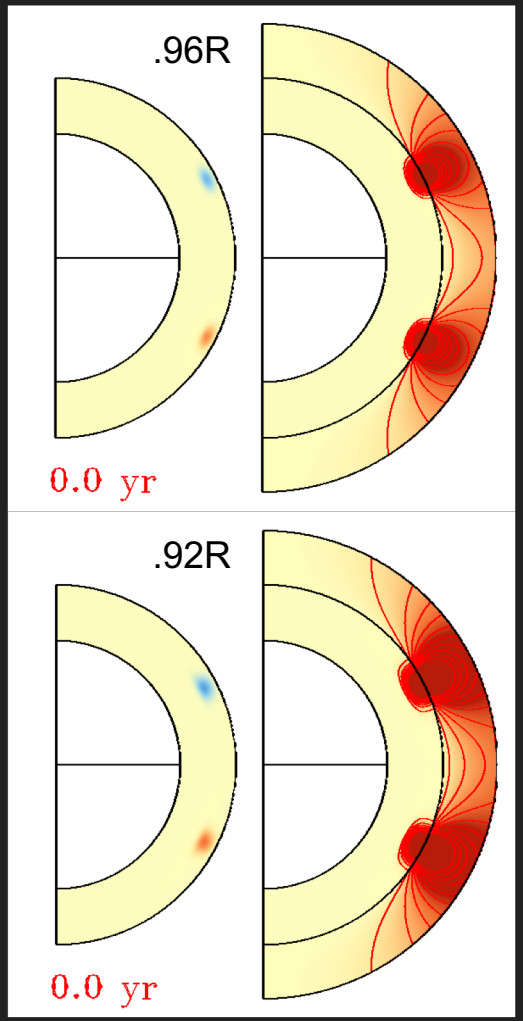
Two Bipolar Spots

- +/- 25 degrees latitude
- Flux: 3.56*10^22 Gauss
- Tilt is given by Joy’s law

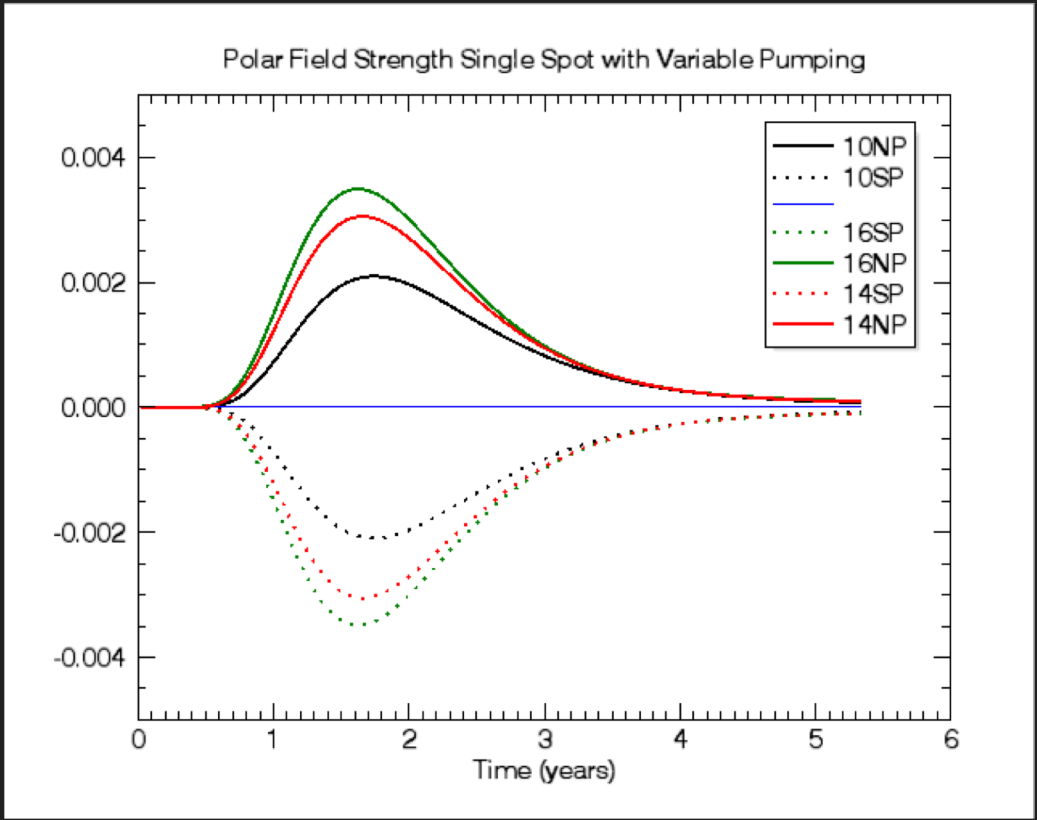


Sunspot Depth



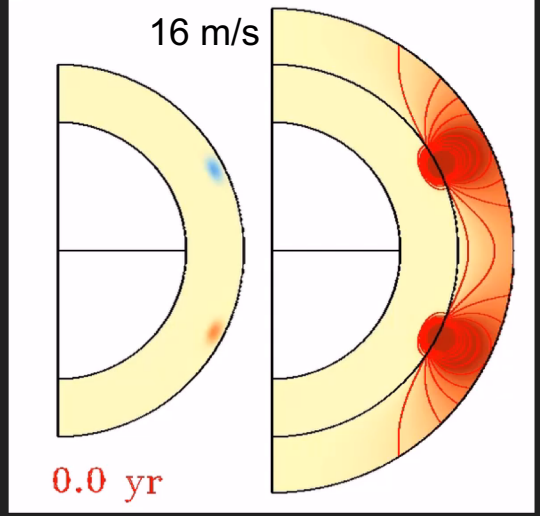


Magnetic Pumping

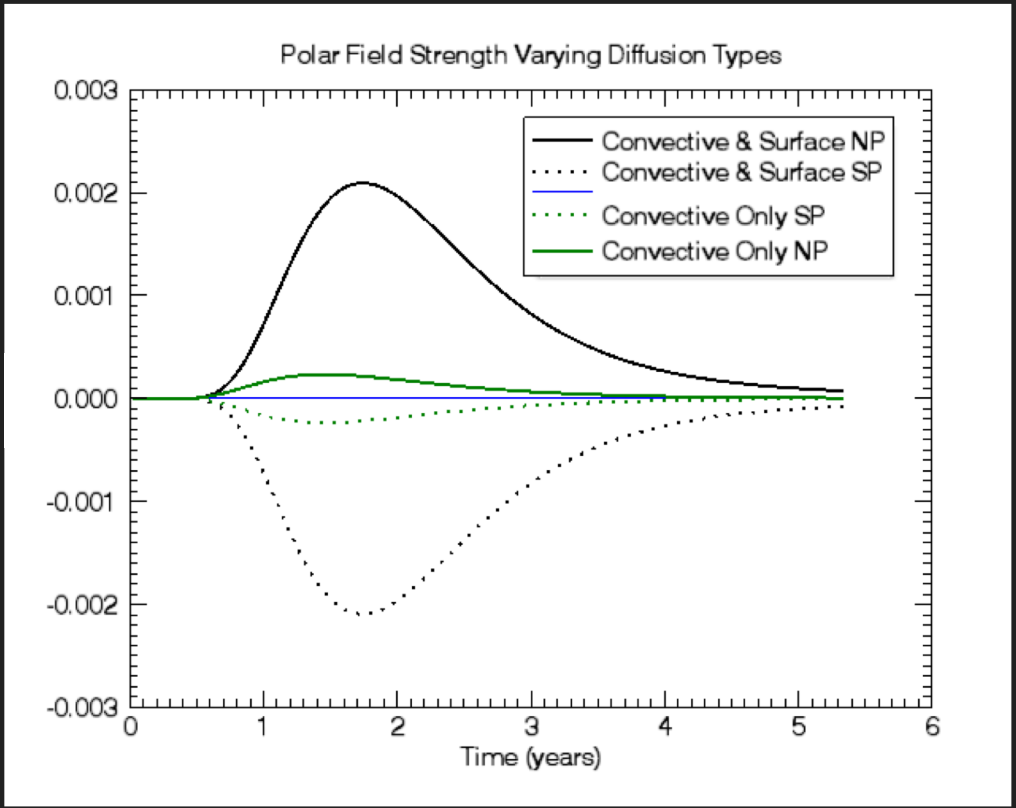


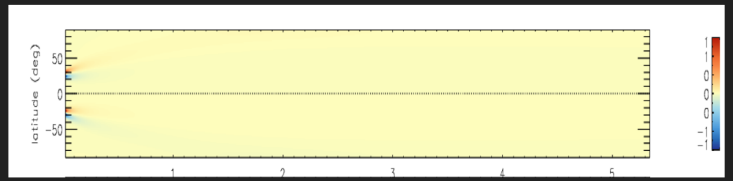
10 m/s

16 m/s

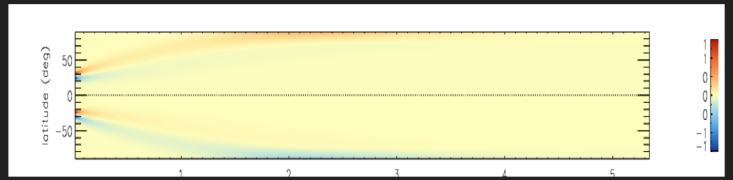


Diffusivity



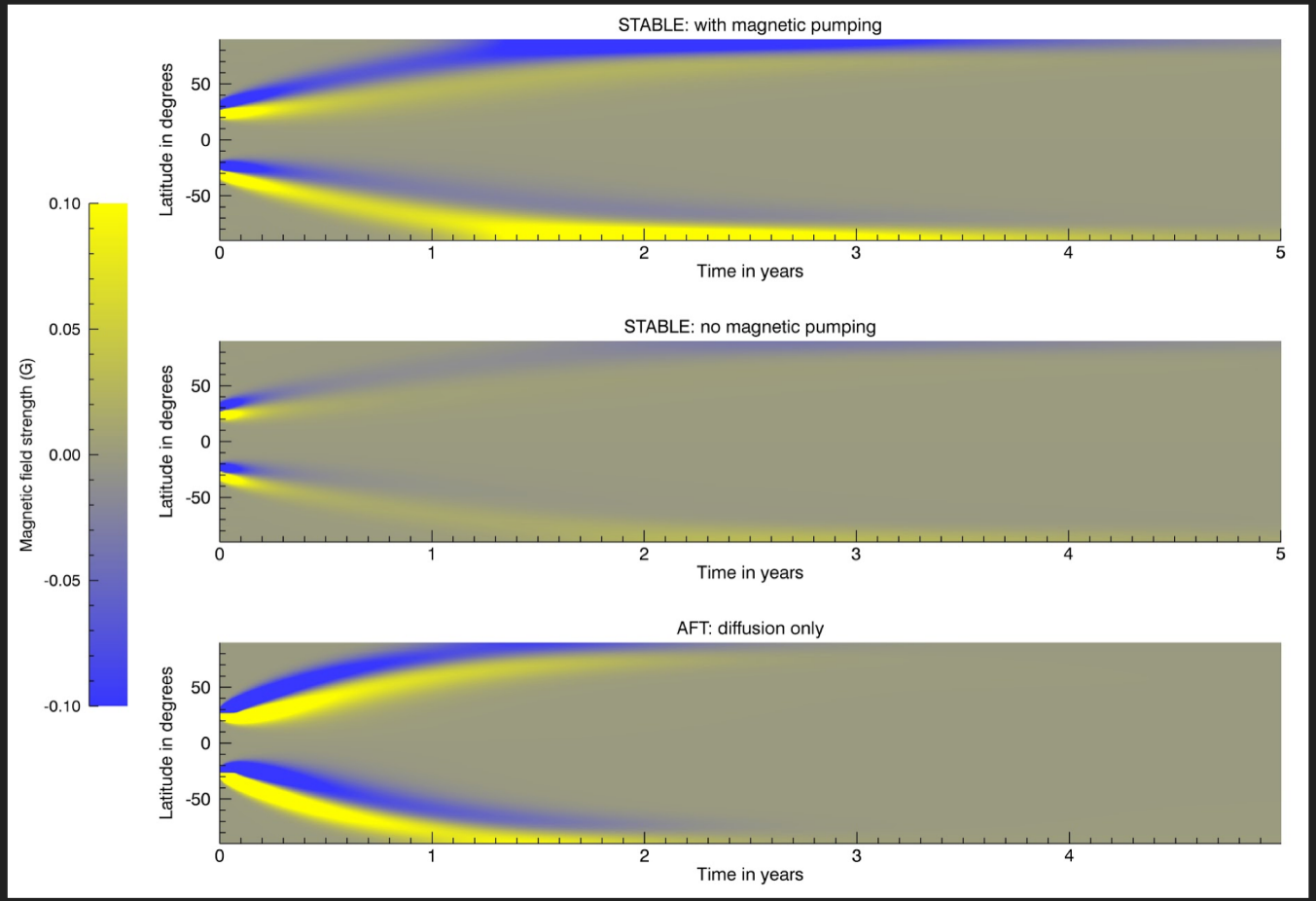


Convective Only

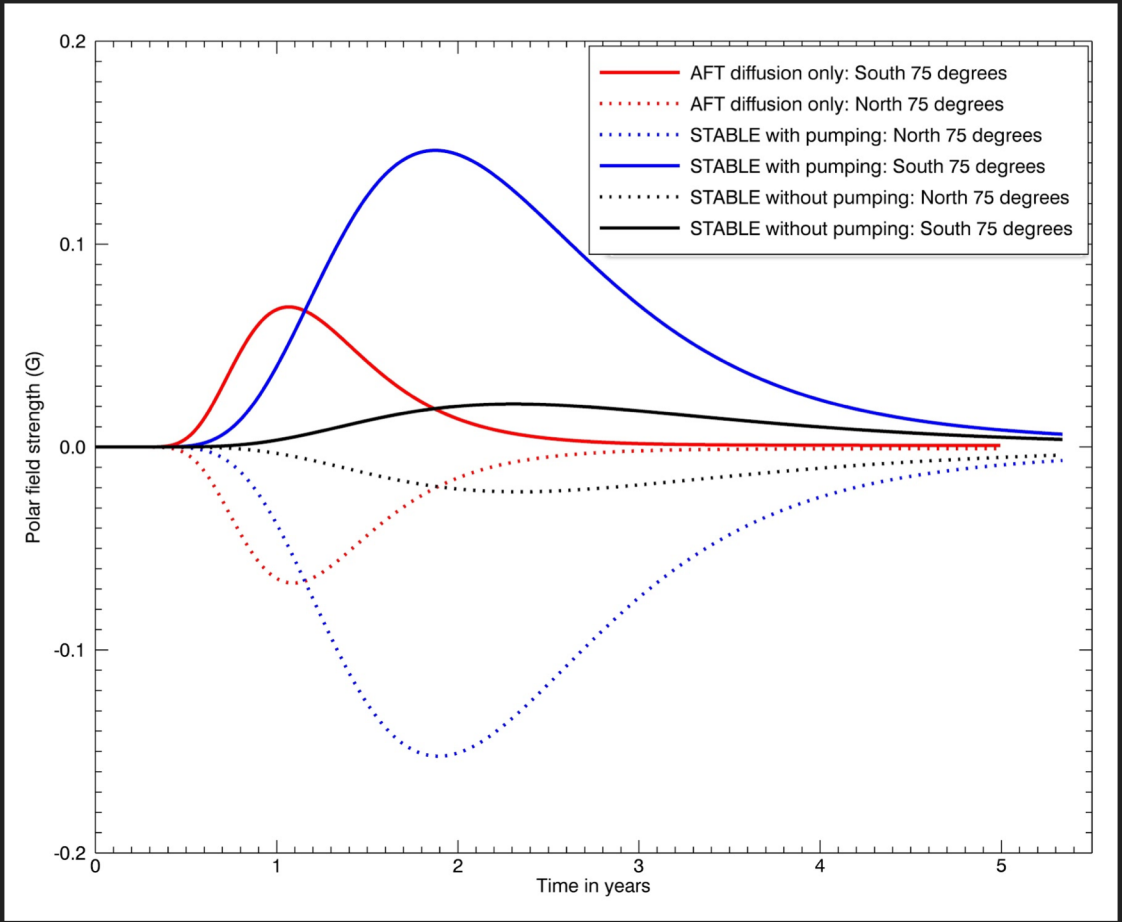


Convective and Surface

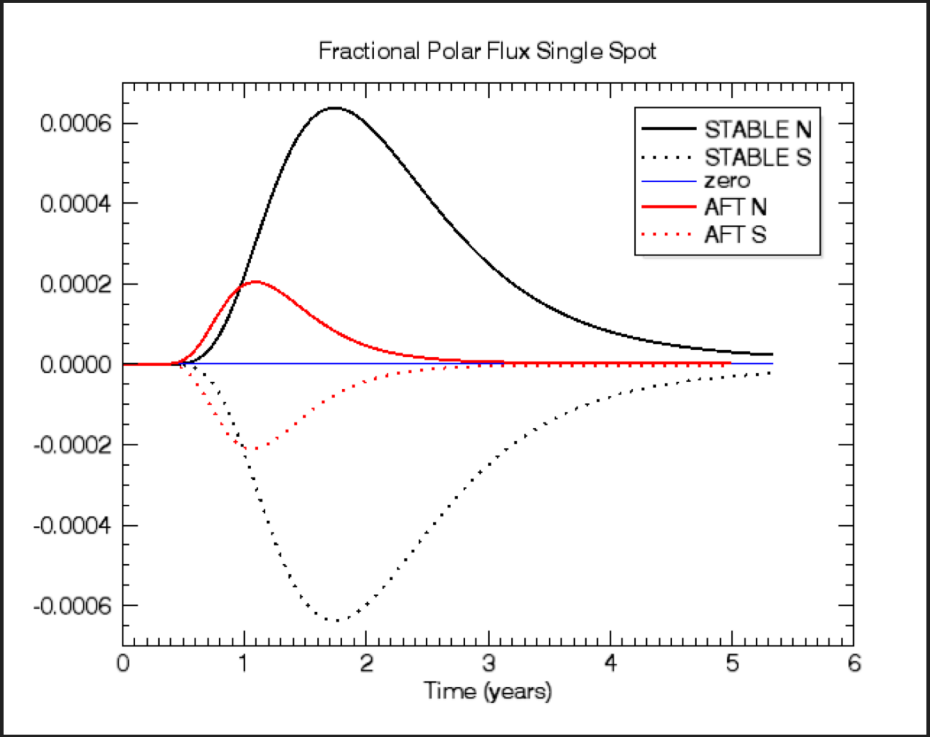
Single active region



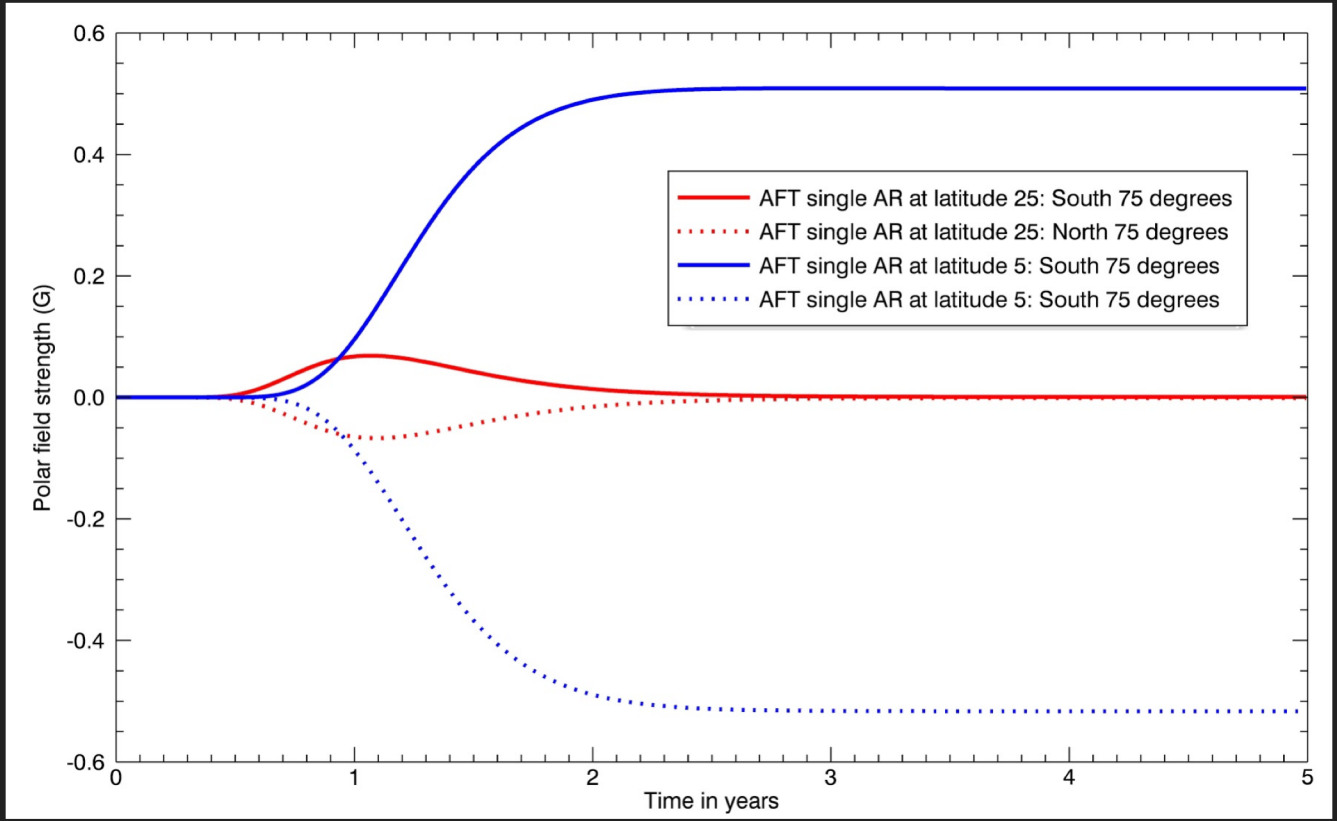
Single active region



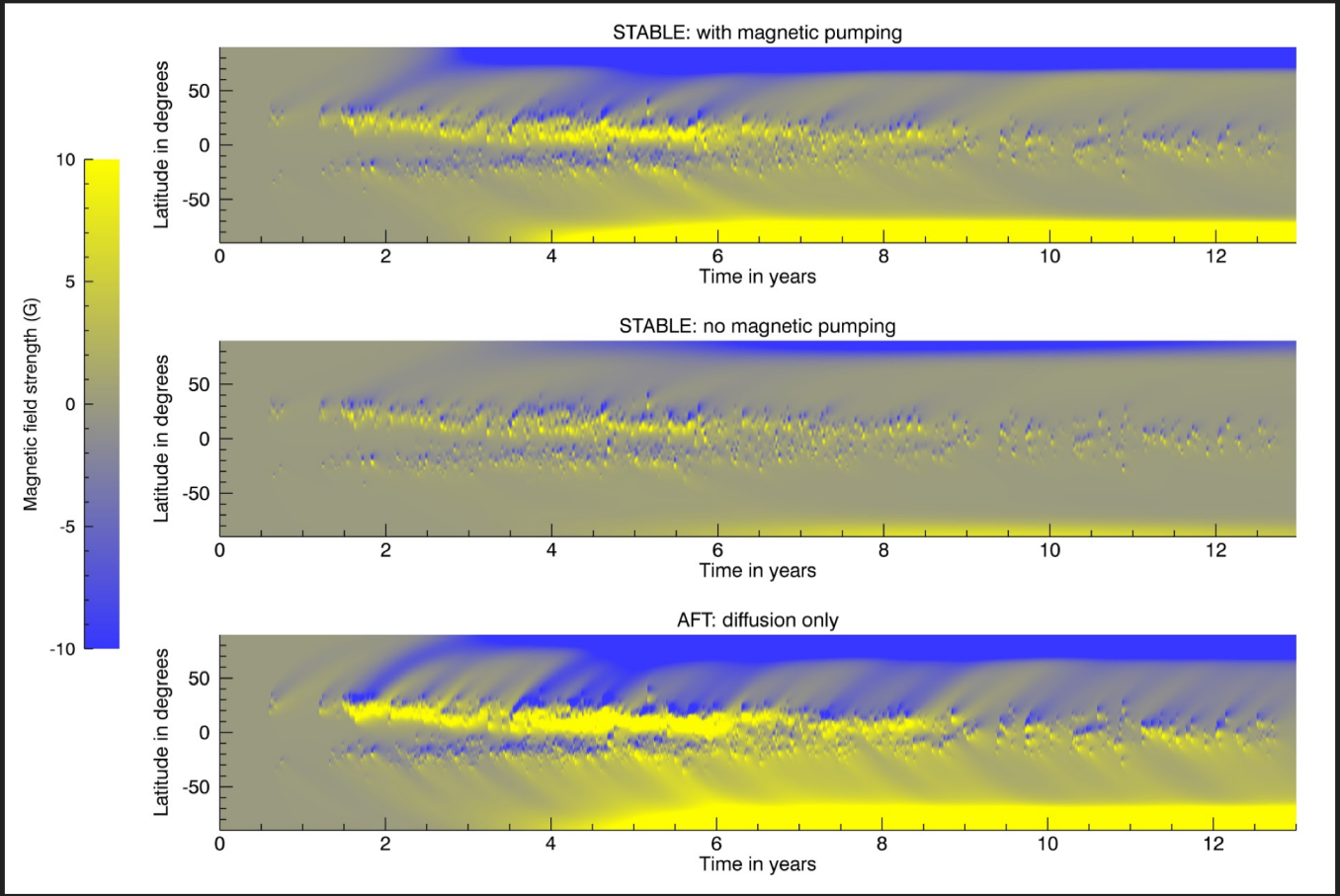
Fractional Polar Flux



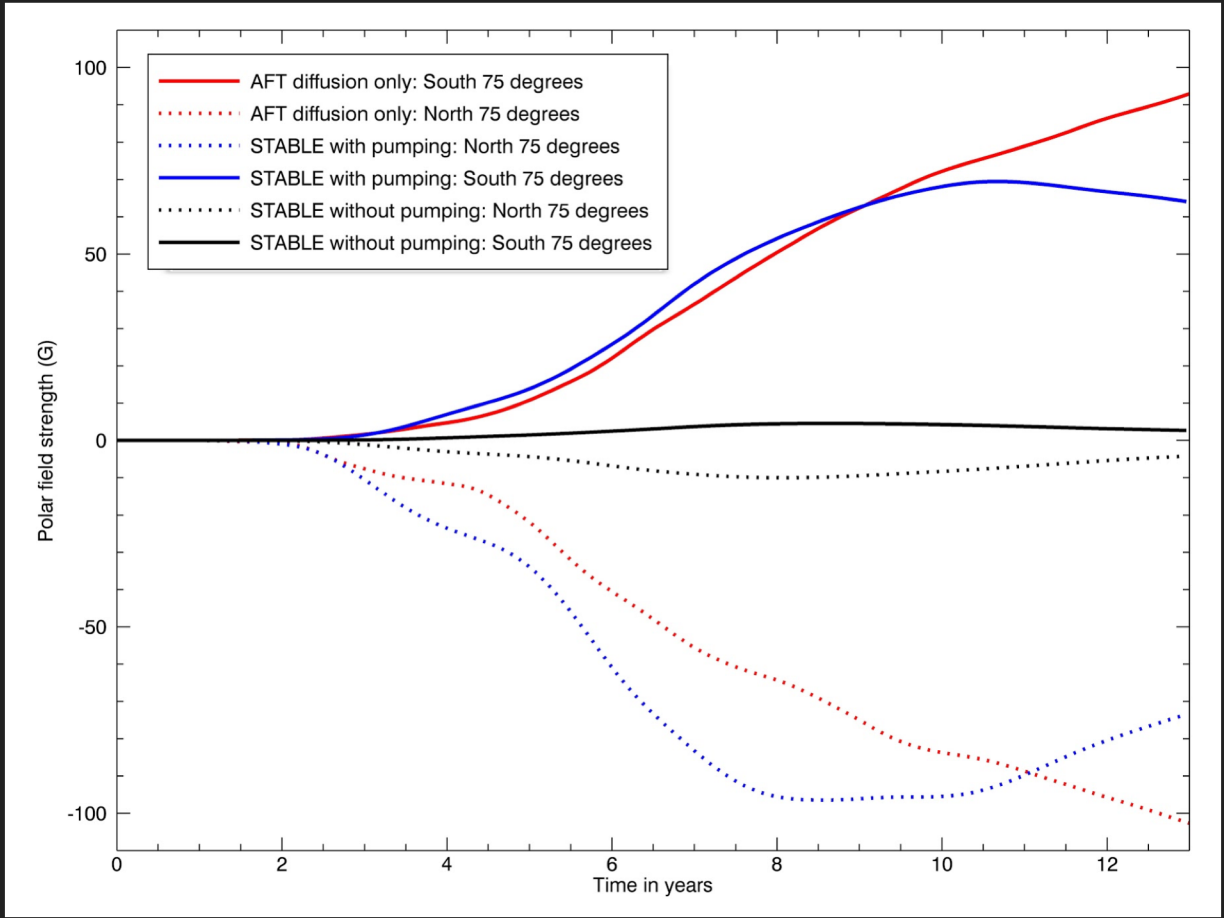
Different latitudes with AFT



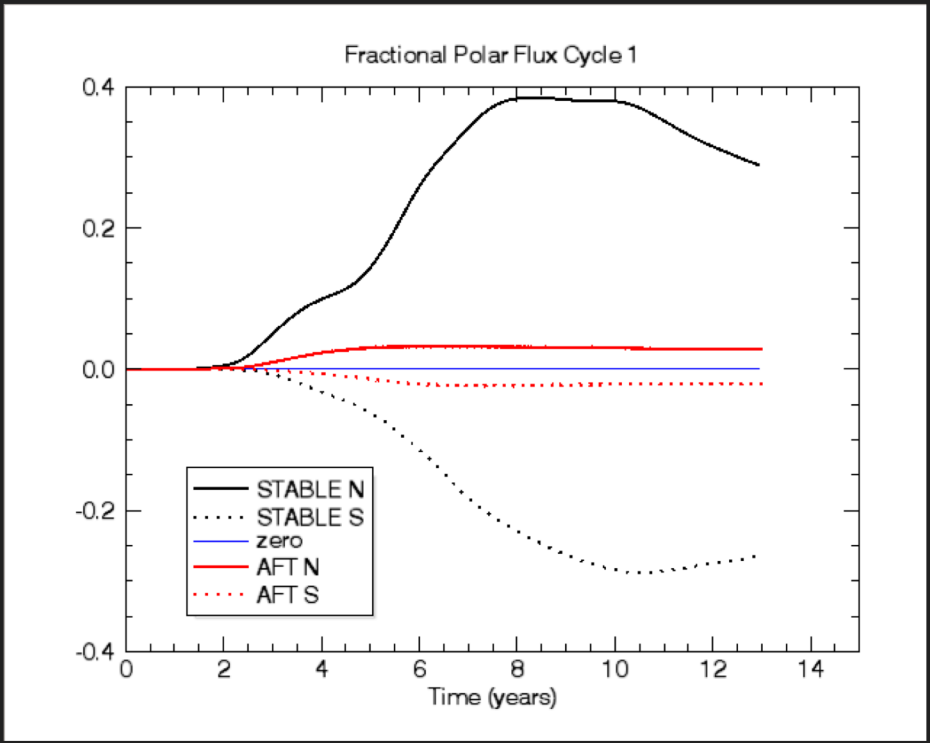
Full synthetic Active Region database



Full synthetic Active Region database



Fractional Polar Flux



Conclusions

- A comparison turns out to be tricky!
- Can make the models similar on the surface - but …
- AFT - leading & trailing polarities aren’t connected
- In STABLE they are - the workings of the convective zone will affect the surface flux transport

Future Work

- Continue tuning spot depth and pumping in STABLE to better match AFT
- Analyze AFT's diffusive and convective cases by running varying diffusivities
- Comparing with observation: Convective STABLE
- Verify flux input

Thank you!