Impact of an L5 Magnetograph on Non-Potential Solar Global Magnetic Field Modeling

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Outline

- Part 1 : Overview

    Space Weather
    Coronal Mass Ejections
    L5 mission (Carrington/Lagrange)

- Part 2: Model

    Global Non-Potential Simulations.

- Part 3: Improvements in Global Modelling with L5 Magnetograph

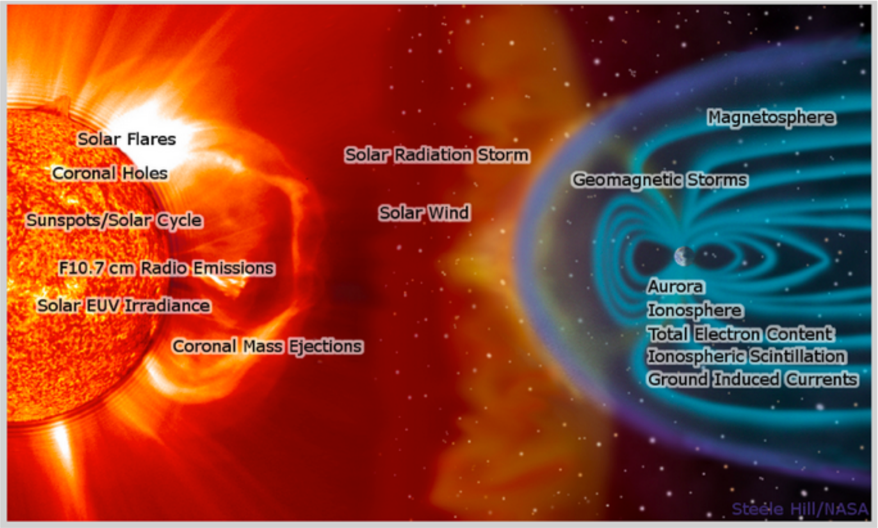
    Three simulations: Reference Sun
    L1 only
    L1 and L5

- Summary and Future Studies.

- Published Results: Mackay, Yeates and Bocquet, (2016), ApJ, 825,131

Space Weather

- Space Weather (SW) : describes a wide range of possible phenomena that originate on the Sun but have consequences at the Earth.



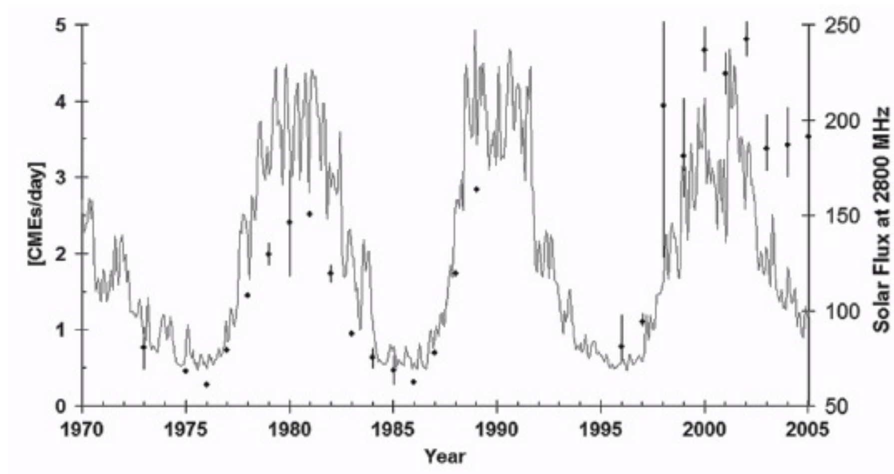
- Overview of Space Weather: COSPAR and ILWS road map (Schrijver et al. 2015).

Solar Origin	Effect at Earth
Solar Flares	Ionisation of atmosphere & Radio Blackouts
Coronal Mass Ejections (CMEs)	Geomagnetic Storms & Ground Induced Currents & Effect of GPS and GNSS
EUV Irradiance	Heats upper atmosphere (spacecraft drag)
CH/Open Flux/Solar Wind	IMF, magnetopause, Heliospheric Current Sheet, CIR
SEPs	Damage Satellite Electronics & Danger to Manned Missions.

Coronal Mass Ejections

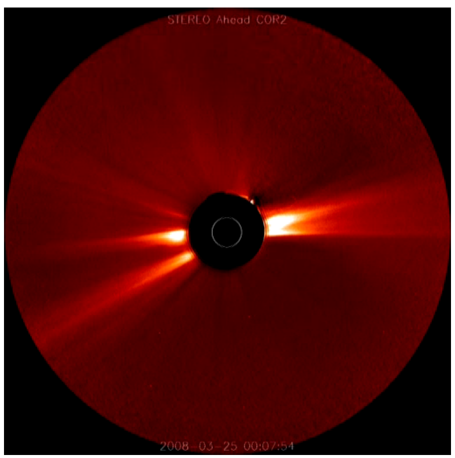
- Ejection of mass and magnetic field from the Sun
  - speed ~ 100-3000km/s
  - Mass ~ 1.6×10^{12} kg
  - mean transit time ~ 3 days
  - cause severe space weather events

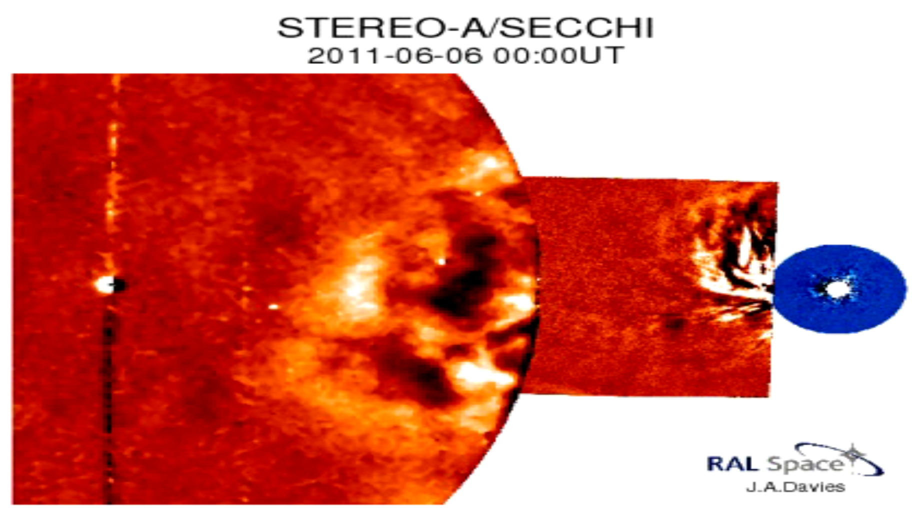
(Forbes et al. 2006,
Webb and Howard 2012- OBS
Chen 2011 - Theory)



(Cremades and St Cyr 2007)

STEREO – COR 2





- Origin of CMEs: many theories ~ non-potential fields (free magnetic energy, electric currents).

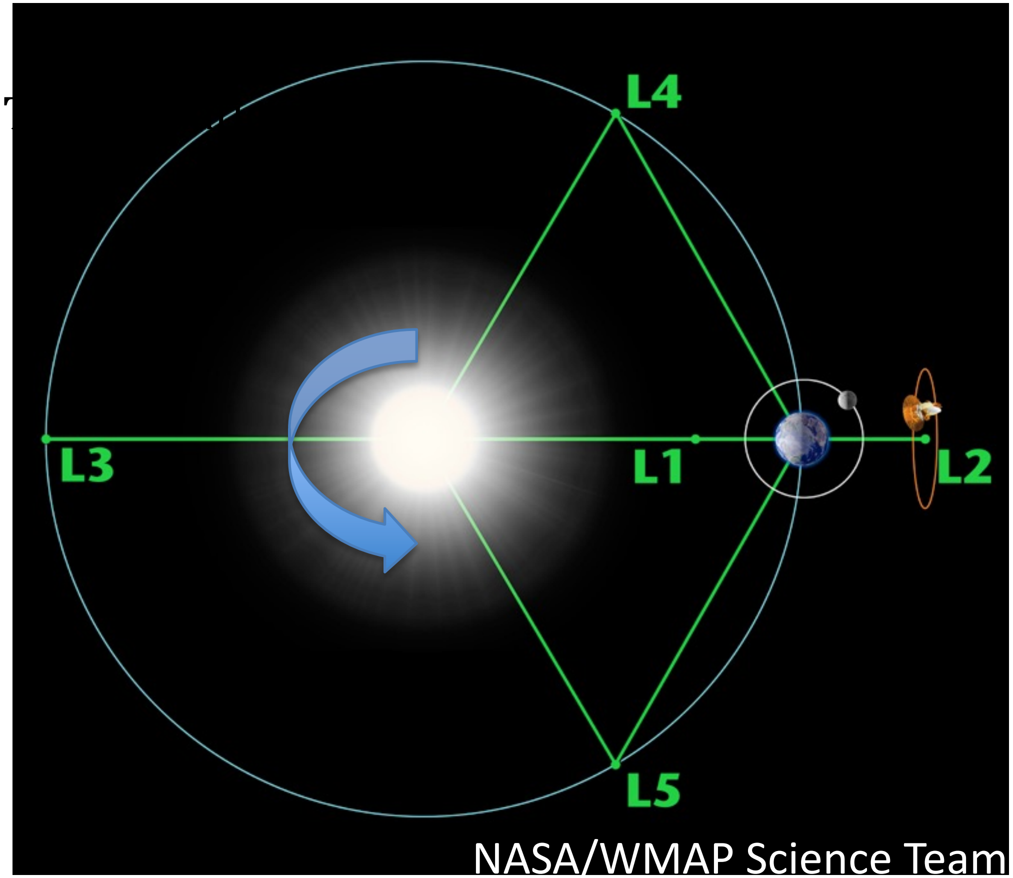
L5 Mission Concept

- L5 mission planned as an operational Space Weather mission: early study stage.

  http://www.esa.int/Our_Activities/Space_Safety/Lagrange_mission
  https://www.metoffice.gov.uk/weather/learn-about/space-weather/l5-mission

- Place satellite with remote sensing and in-situ instruments at the L5 points 60° behind Earth (increased coverage of Sun)

- Complements similar instrument at L1.

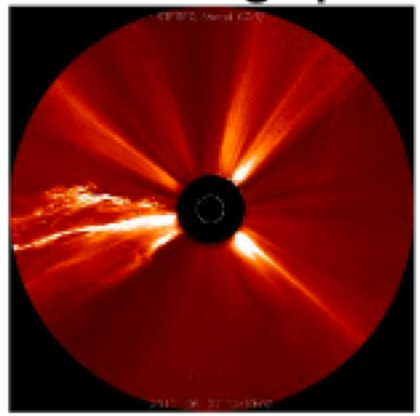


- Possible payload – see working group pages for more update info.

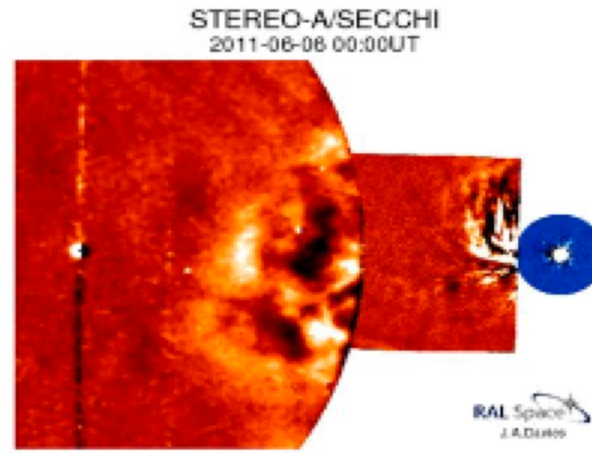
- Remote sensing
  - Coronagraph
  - Heliospheric Imager
  - EUV Imager
  - X-Ray Flux Monitor
  - Magnetograph

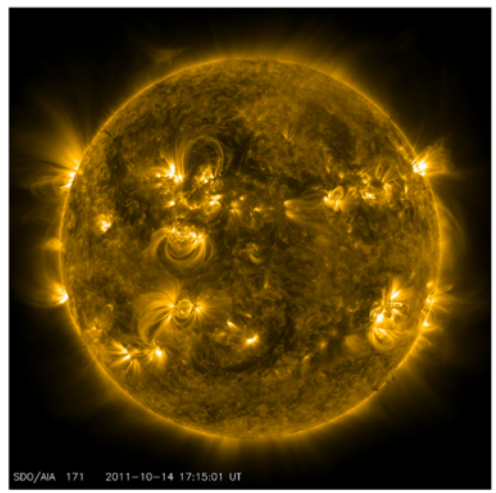
- In-situ
  - Magnetometer
  - Plasma Instruments

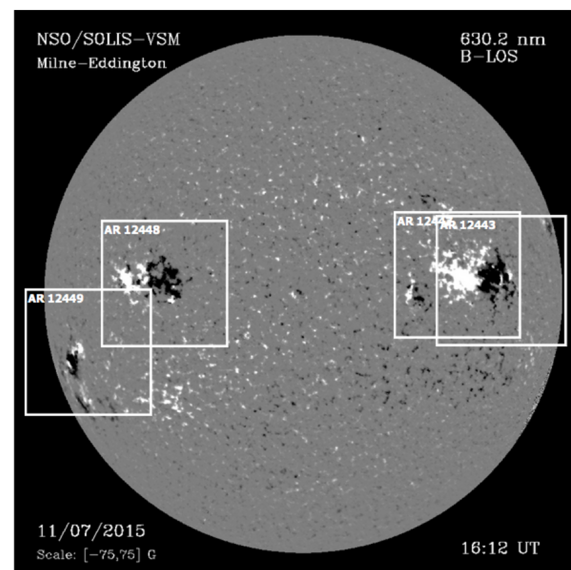
Coronagraph



Heliospheric Imager







Key Questions

- Can a L5 magnetograph improve our understanding of global non-potential fields on the Sun ?

- If so, how much of an improvement can we expect ?

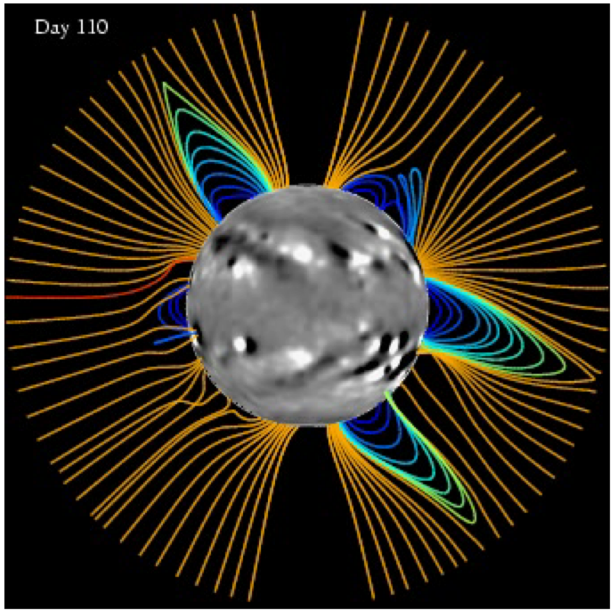
Part 2: Global Non-Potential Model

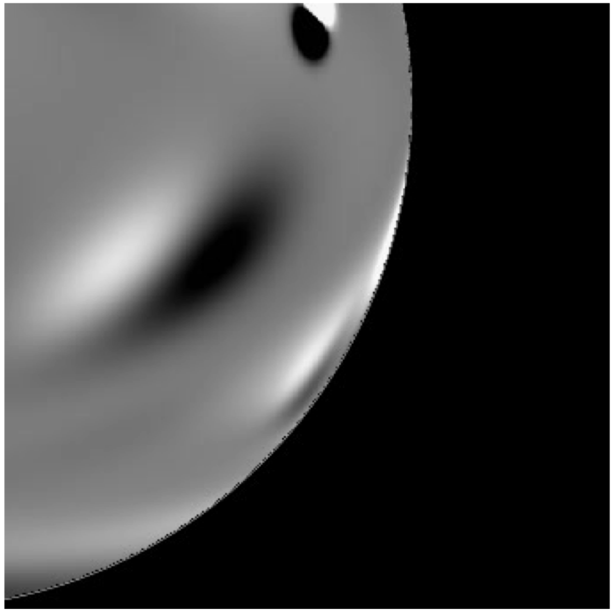
- Long Term continuous simulations (months to years).
  - Build up free magnetic energy and helicity.

- Two coupled components:

Photosphere: Flux Transport Model
- simulates evolution of B_r on Sun.
- includes flux emergence (+/- ve helicity).

Corona : Magnetofrictional Relaxation
- quasi-static evolution
- non-linear force-free states, $\mathbf{j} \times \mathbf{B} = 0$
- development of sheared fields along PIL (van Ballegooijen and Martens 1989)





- Development and Application:
  van Ballegooijen et al 2000;
  Mackay and van Ballegooijen 2006a,b;
  Yeates et al. 2007, 2008a,b, 2009a,b.

Two Component Model

- Evolve, Suns large-scale field, **B,** through the induction equation.

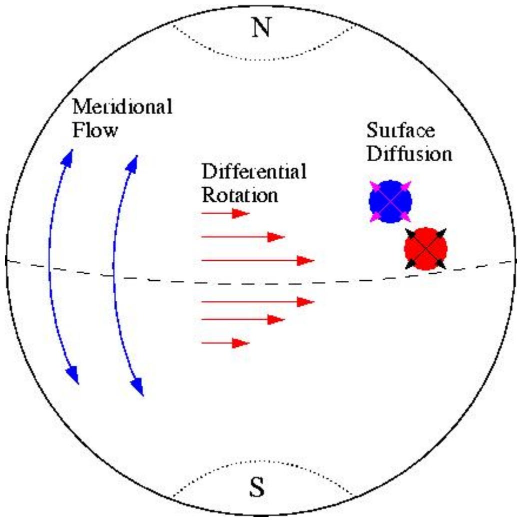
$$B = \nabla \times A$$

- Photospheric BC : Flux Transport Model

Differential Rotation $\tau_\Omega = \frac{2\pi}{\Omega(\frac{\pi}{2}) - \Omega(0)} = 0.25\text{years}.$

Meridional Flow $\tau_{mf} = \frac{R_\star}{u_o} = 2\text{years}.$

Surface Diffusion $\tau_D = \frac{R^2}{D} = 34\text{years}.$



$$\frac{\partial A_\theta}{\partial t} = + u_\phi B_r - \frac{D}{r \sin\theta} \frac{\partial B_r}{\partial \phi},$$

$$\frac{\partial A_\phi}{\partial t} = - u_\theta B_r + \frac{D}{r} \frac{\partial B_r}{\partial \theta},$$

Shears the surface fields ~ coronal field diverges from equilibrium.

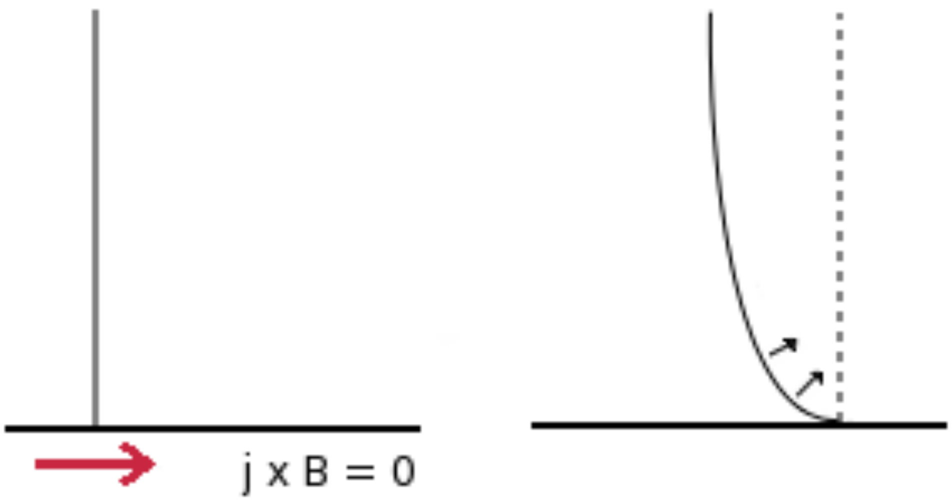
Physical time scale.

- Coronal Model : Magneto-Frictional Relaxation (velocity $\propto$ lorentz force.)

$$\frac{\partial \mathbf{A}_0}{\partial t} = \mathbf{v}_0 \times \mathbf{B}_0 - \mathbf{E}_0,$$

$$\mathbf{E}_0 = -\frac{\mathbf{B}_0}{B_0^2}\nabla \cdot \left(\eta_4 B_0^2 \nabla \alpha_0\right), \quad \alpha_0 = \frac{\mathbf{B}_0 \cdot \mathbf{j}_0}{B_0^2} \qquad \mathbf{v}_0 = \frac{1}{\nu}\frac{\mathbf{j}_0 \times \mathbf{B}_0}{B_0^2} + v_{\mathrm{out}}(r)\mathbf{e}_r.$$

Coronal field evolves through a series of quasi-static force-free states **(j** x **B = 0).**



Relaxation time scale ~ not physical.

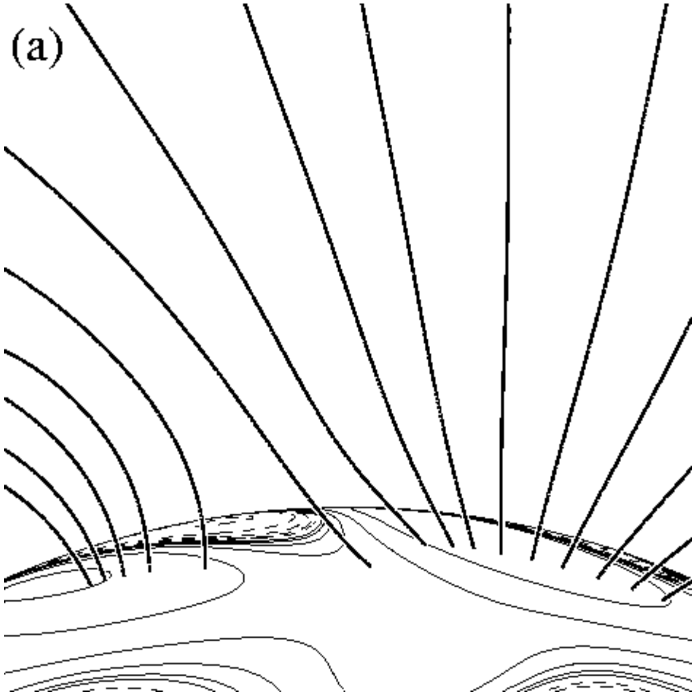
Alt. non-ideal term

$$\eta(|\mathbf{j}|) = \eta_o\left(1 + c\frac{|\mathbf{j}|}{B_{max}}\right)$$

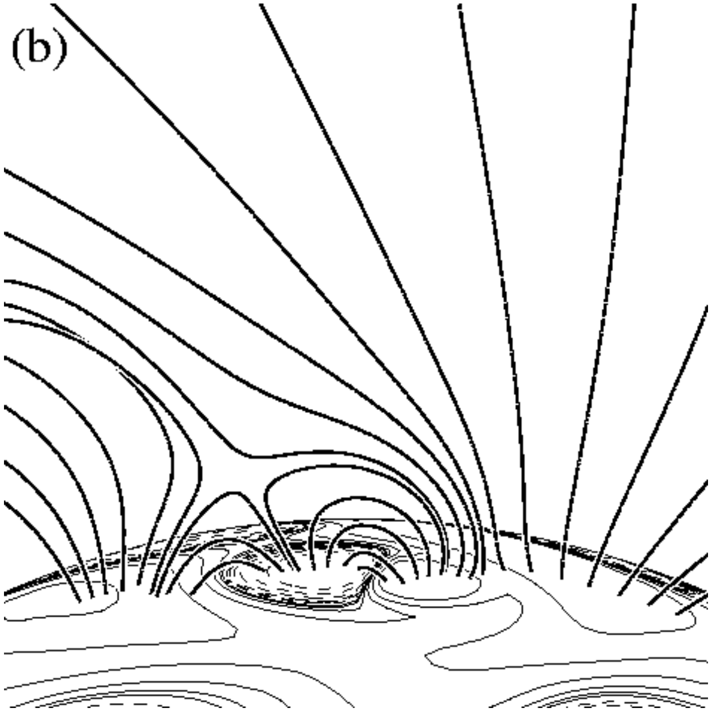
$$\eta_o = 0.1D, \quad D = 600km^2s^{-1}, \quad c = 0.2$$

Flux Emergence

- Bipoles are inserted as an isolated field containing either zero, +ve or –ve helicity (alpha) both in the photosphere and corona.



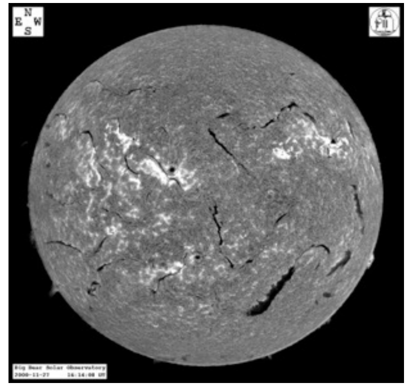
Pre-existing Field

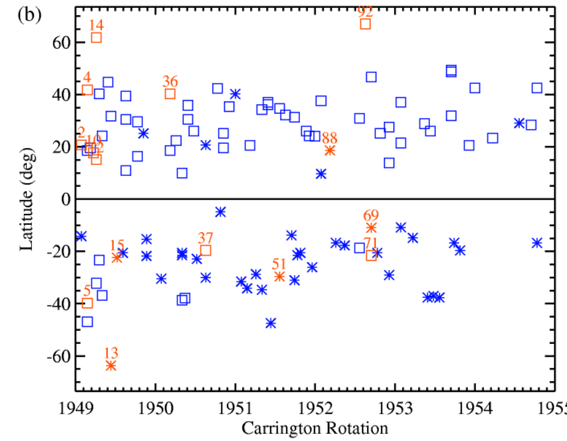


New Emergence

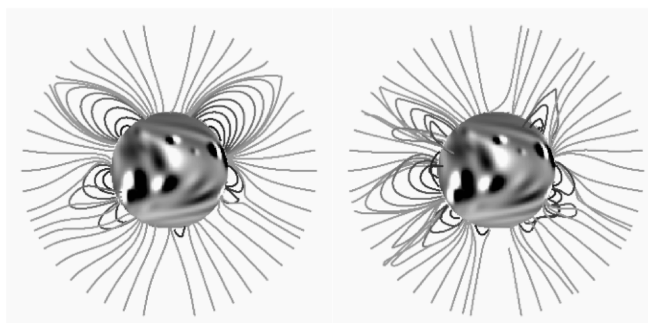
Previous Applications

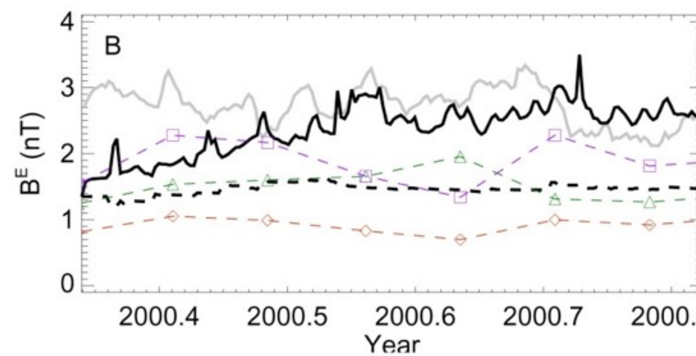
- Chirality and helicity in solar filaments : blue correct, red incorrect (Yeates, Mackay and van Ballegooijen).



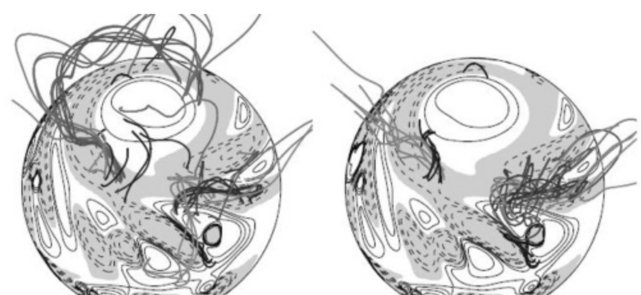


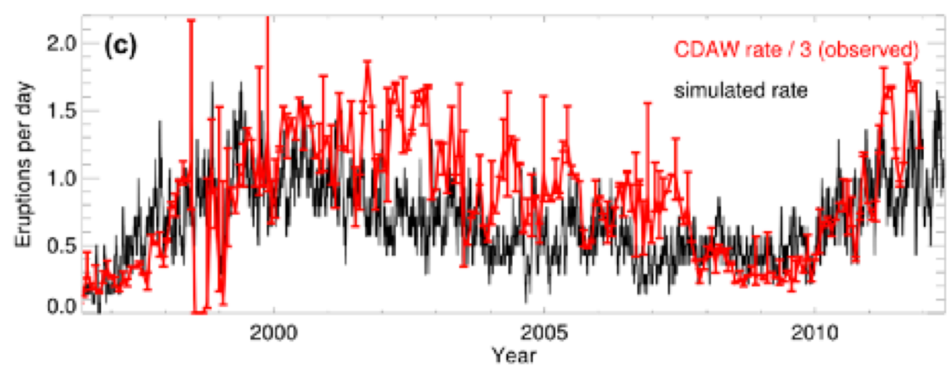
- Improved Open Flux compared to PFSS models (Yeates and Mackay 2010).


(a) PFSS
(b) Flux transport and magneto-friction



- Flux rope ejection/CME rates (Yeates 2014)


(e) Day 205
(f) Day 206



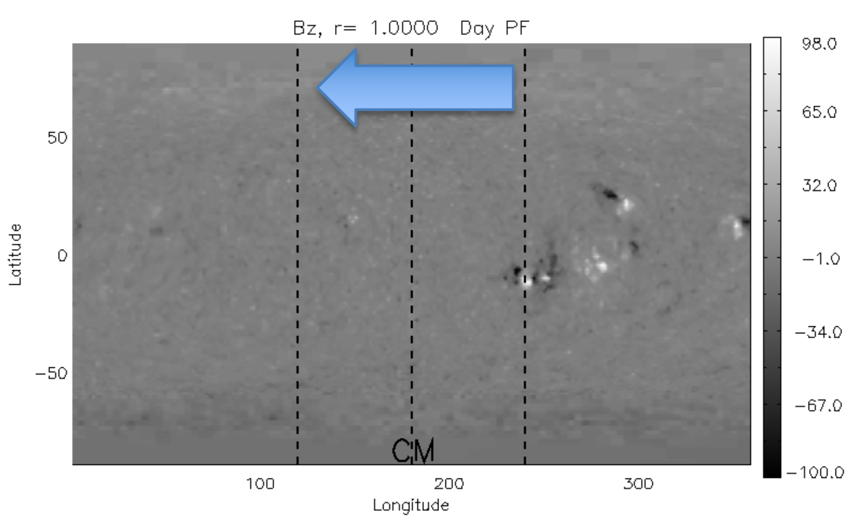
Stage 3: Simulations

- Aim: Determine what effect having increased magnetogram data will have on accuracy of global NLFFF simulations - three simulations

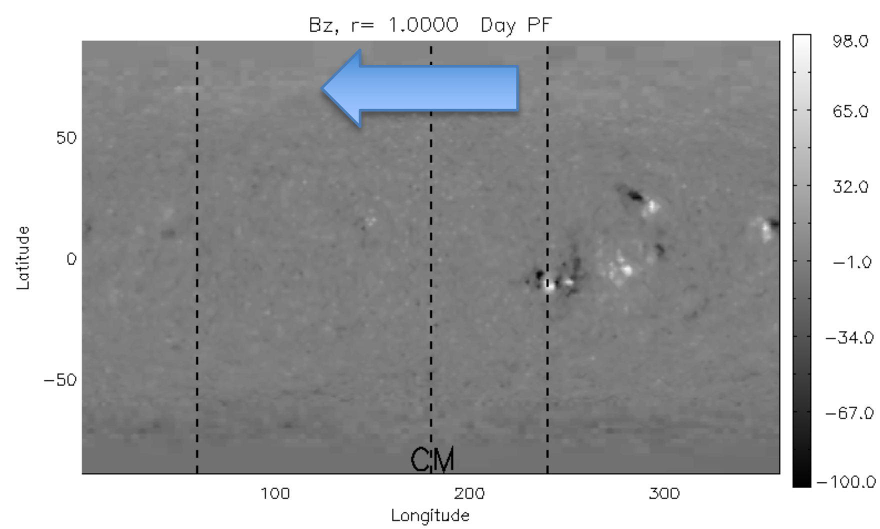
1. Reference Simulation: 22yr 3D NLFFF simulation with random emergences of bipole at all longitudes (“real Sun”).

2. Limited Data simulations: 22yr simulations but bipole emergences limited to FOV – taken to be 30^{o} from limb.

Earth based



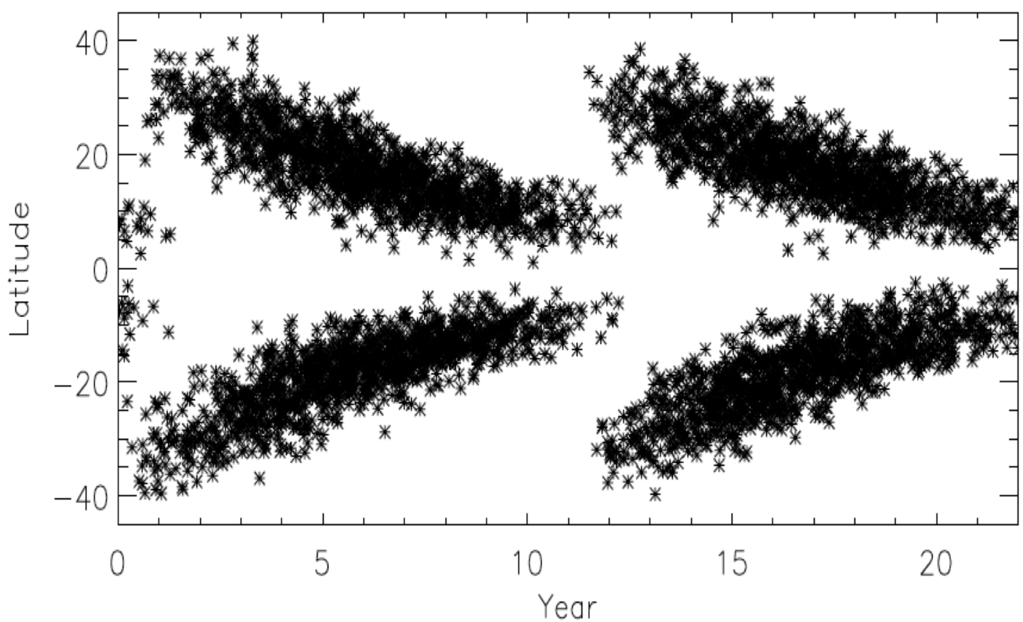
Earth & L5

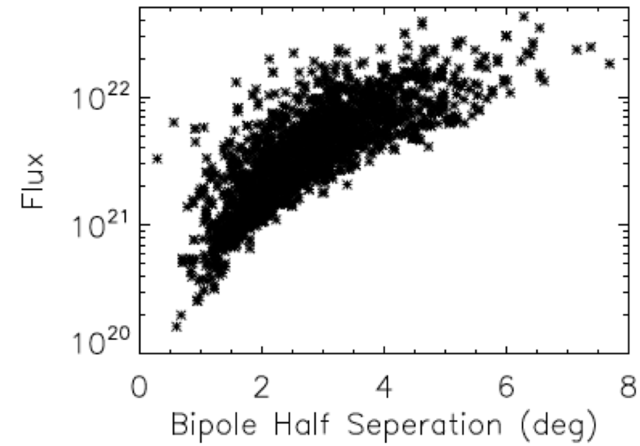


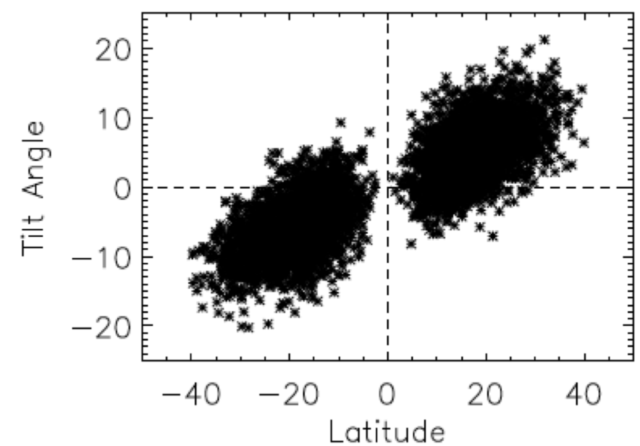
Stage 3: Reference Sun Simulation

- Construct a reference data set:
  - 360° magnetograph coverage of Sun- theoretical bipole data set
  - 22yr 3D NLFFF simulation (emergences of bipole at all longitudes)
  - Best representation of “Real Sun”
  - IC potential field
  - No. of Bipoles : 4770

    Flux Emerged : 3.21 e25 Mx

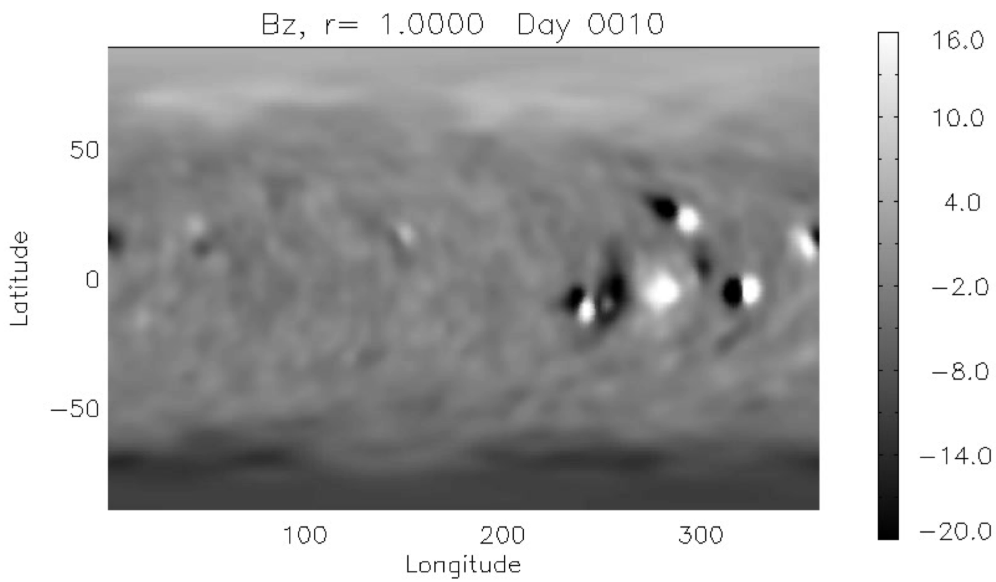


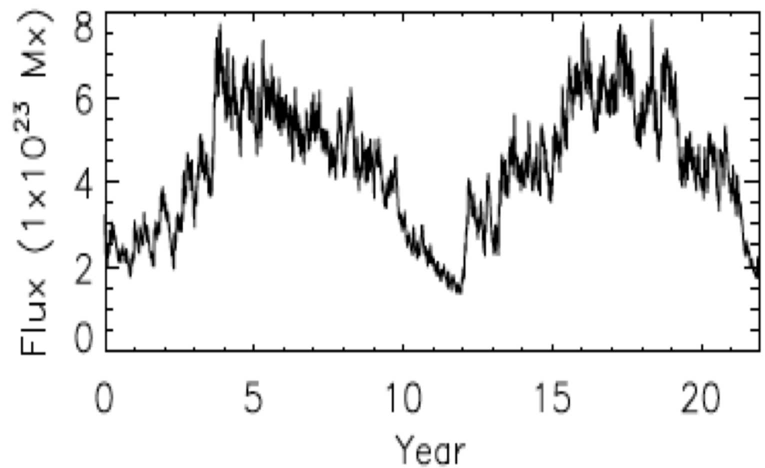


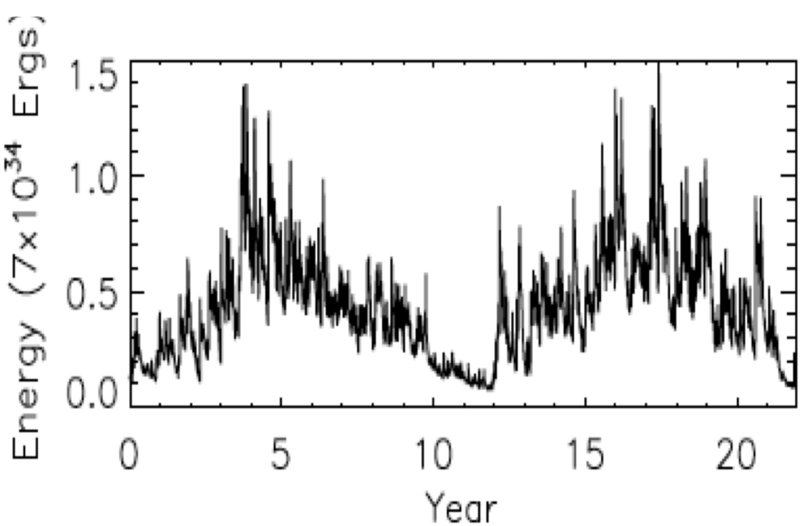


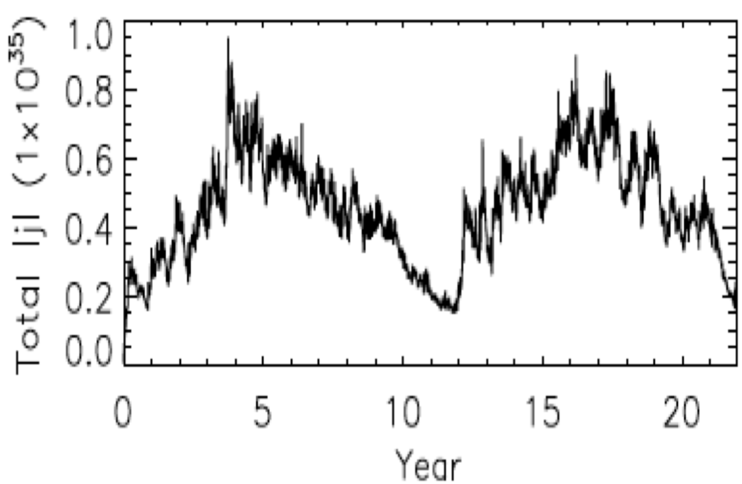
Reference Sun Properties

- Evolution of Br at photosphere and global integrated quantities.



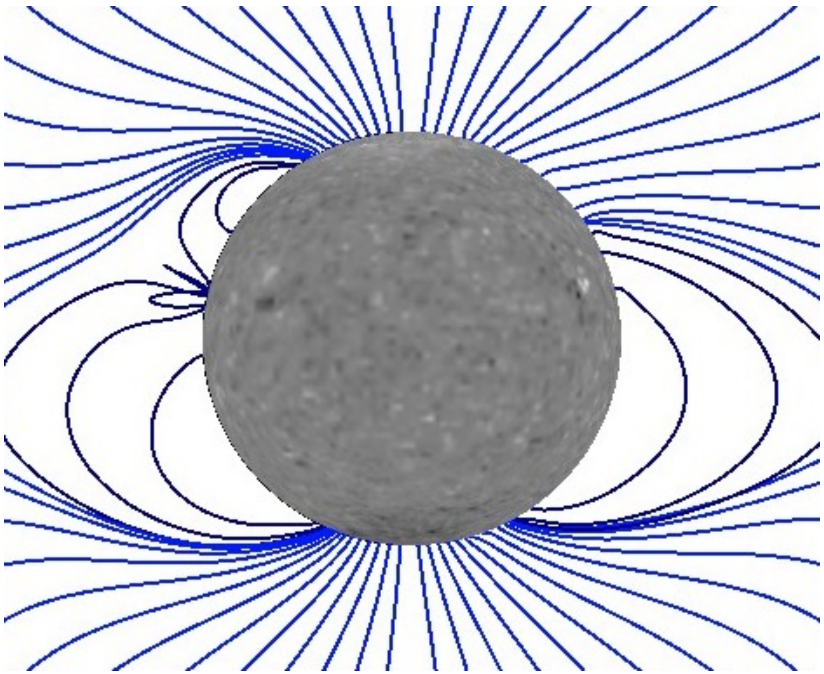






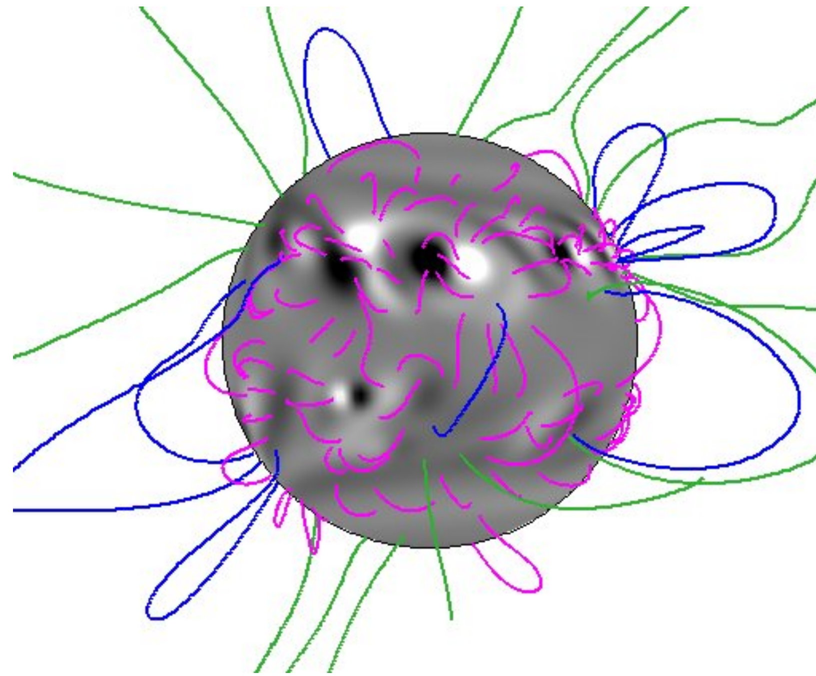
- Example Coronal Field

Day 0



Potential Field

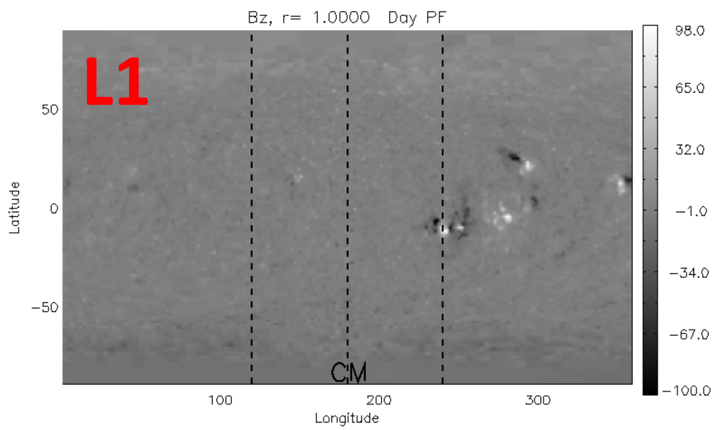
Day 1800

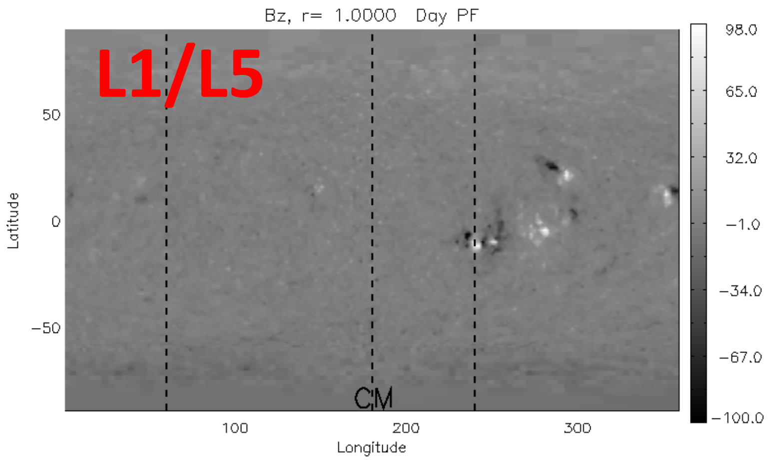


NLFFF

Limited FOV Simulations

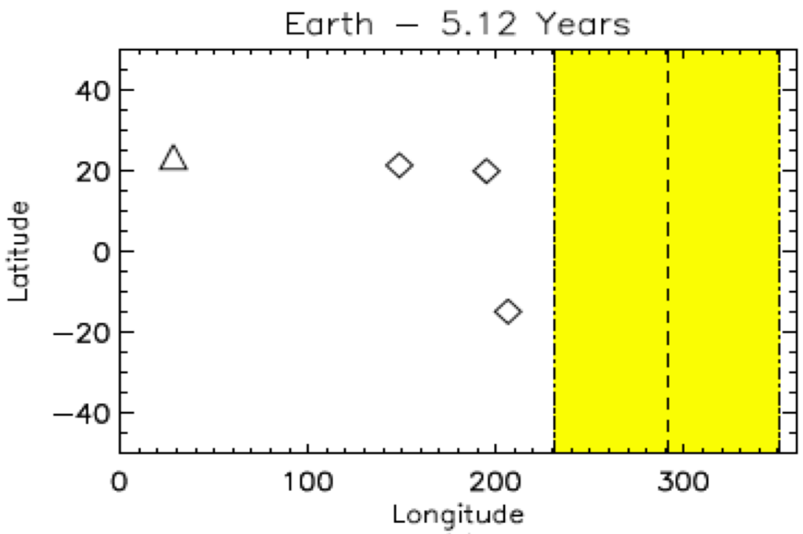
- Consider present circumstances: limit FOV of the Sun.



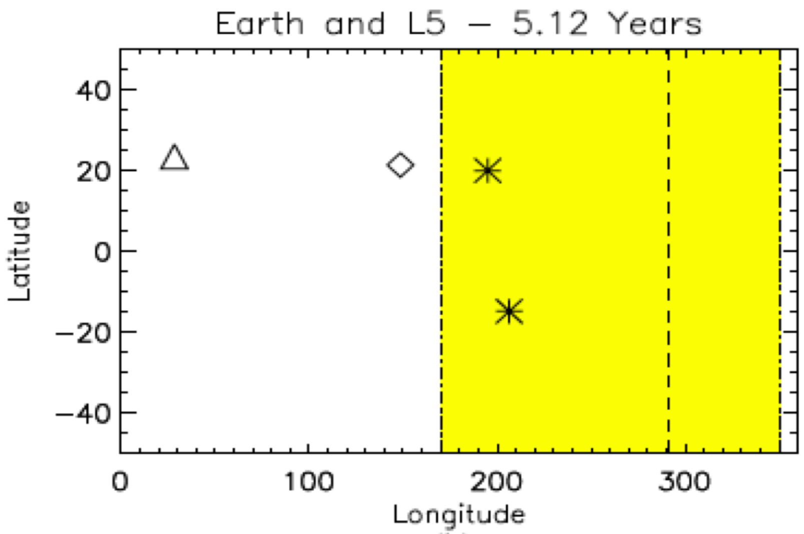


- Use Reference Sun simulation as limited FOV magnetograph observations: L1 and L1/L5
- Identify bipole emergences in limited lon. range.
- Repeat 22yr 3D non-potential simulations with limited FOV bipoles.

Illustration of Bipole Identification



(a)



(b)

- Reference Sun:
  4 bipoles emerge (ϕ : 20-210)
  CM ~ 291°
- L1 (Earth): FOV CM-60° – CM+60°

  Rot ~ 3 (1.22,2.0,5.6 days), 1 decayed
- L1/L5 : FOV: CM-120° – CM+60°

  Real time ~ 2, Rot. ~ 1 (1.5 days), 1 decayed

- 3 categories of bipoles

  (i) Real Time (*) - emerges in FOV
  (ii) Rotational updates (◇) - bipole emerges outside FOV rotates into FOV.
  (iii) Decayed bipoles(△) – decayed before entering FOV, not included.

Rotational Updates: Evolution of Bipole Parameters

- All late emergences of bipoles must have their properties updated to represent how they would be seen when rotating into the FOV
- Location:

$$\theta_{cen}(t) = \theta_{cen}(t=0) = \theta_{cen} \forall t$$
$$\phi_{cen}(t) = \phi_{cen}(t=0) + \frac{\Omega(\theta_1)+\Omega(\theta_2)}{2} t$$

- Tilt Angle:

$$tan\gamma(t) = \frac{2\rho(0) sin\gamma(0)}{2\rho(0) cos\gamma(0) + r d\Omega t sin\theta_c}$$

$$d\Omega = \Omega(\theta_1) - \Omega(\theta_2)$$

- Seperation:

$$\rho(t) = \sqrt{\left(\frac{\rho(0) cos\gamma(0)}{r sin\theta_c} + \frac{d\Omega t}{2}\right)^2 r^2 sin^2\theta_c + \rho^2(0) sin^2\gamma(0)}$$

- Flux: analytical solution of flux transport equation in lagrangian coordinates.

$$\frac{\partial B_z}{\partial t} = D\left(1+\Omega_o^2 t^2\right)\frac{\partial^2 B_z}{\partial a_1^2} + 2D\Omega_o t \frac{\partial^2 B_z}{\partial a_1 \partial a_2} + D\frac{\partial^2 B_z}{\partial a_2^2}$$

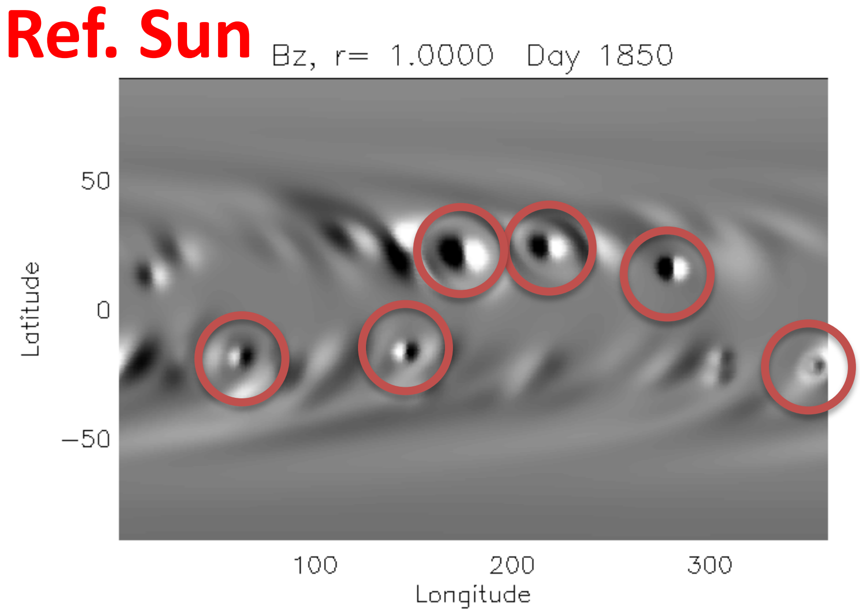
$$\Phi(t) = B_o \rho_o^3 e^{1/2}\sqrt{2\pi}\sqrt{\frac{W}{Q}}$$

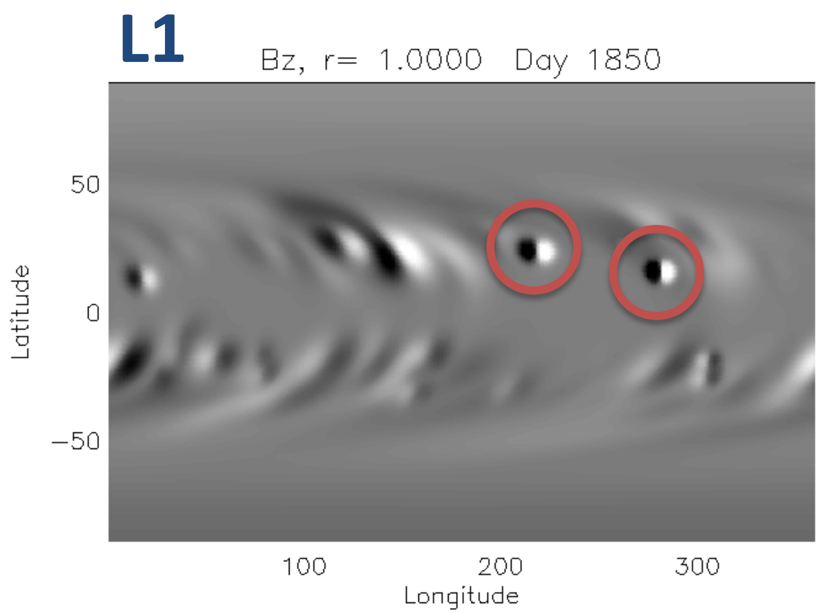
$$Q(t) = 4AC - B^2$$
$$W(t) = A sin^2\gamma_o + B sin\gamma_o cos\gamma_o + C cos^2\gamma_o$$
$$A(t) = \frac{1}{4}\rho_o^2 sin^2\gamma_o + \frac{1}{2}\rho_o^2 cos^2\gamma_o + Dt + \frac{1}{3}D\Omega_o^2 t^3$$
$$B(t) = -\frac{1}{2}\rho_o^2 sin\gamma_o cos\gamma_o + D\Omega_o t^2$$
$$C(t) = \frac{1}{4}\rho_o^2 cos^2\gamma_o + \frac{1}{2}\rho_o^2 sin^2\gamma_o + Dt$$

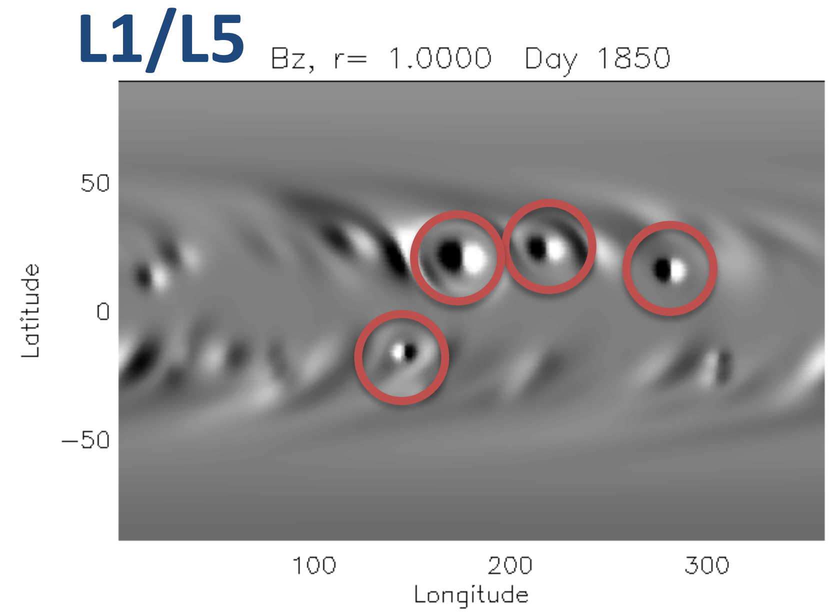
Comparison of Photospheric Field

- Number of bipoles:

Simulation	Real Time	Rot. Update	Missing
L1	1427	1152	2146
L1 & L5	2140	1178	1407

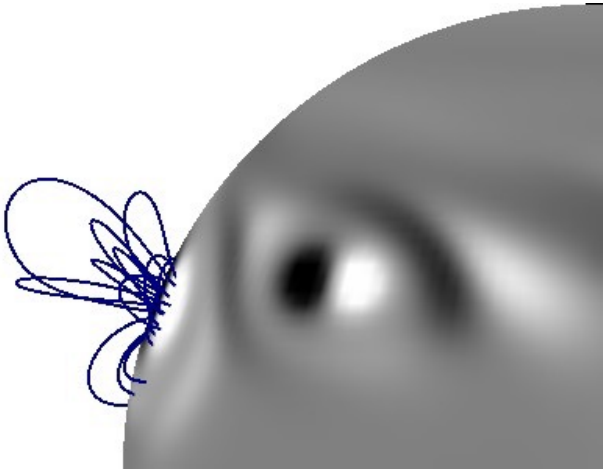




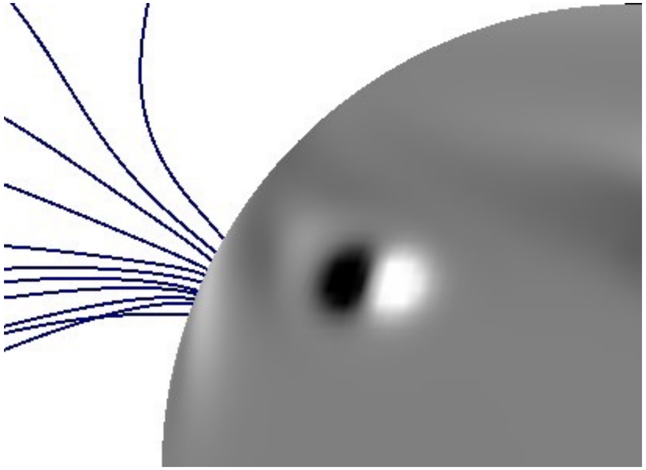


Comparison of Coronal Field

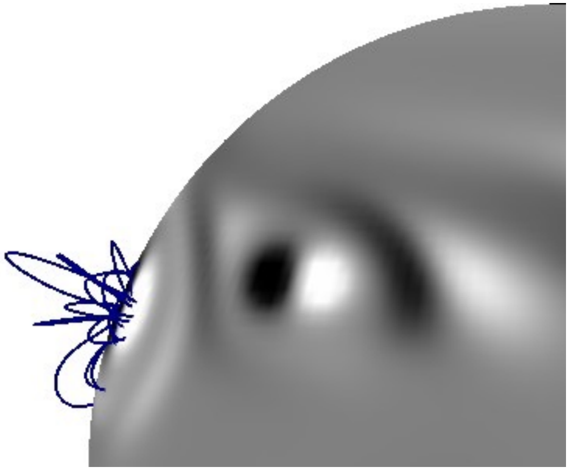
Ref. Sun



L1

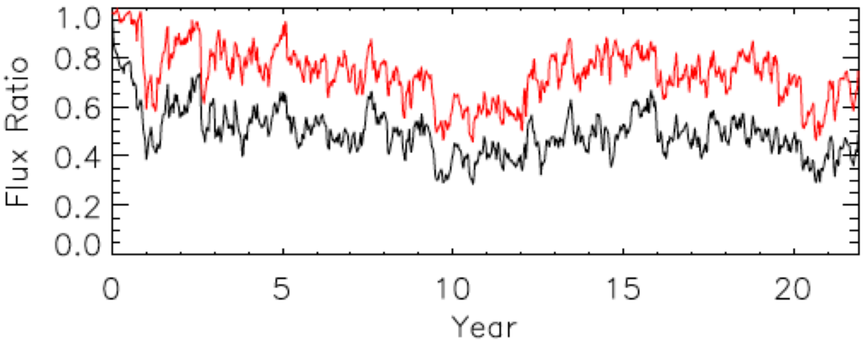


L1/L5

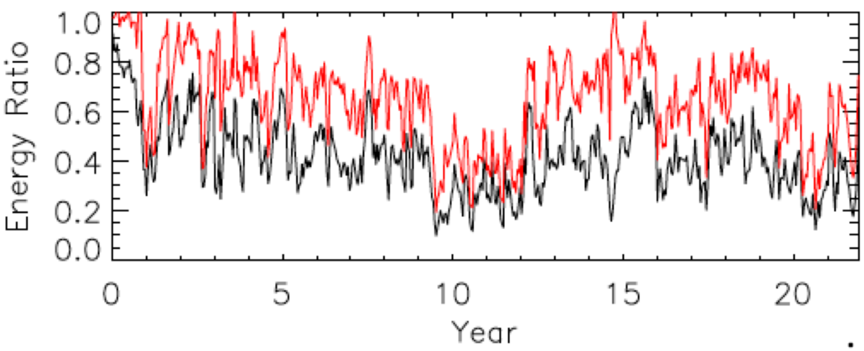


Relative Accuracy of L1 and L1/L5

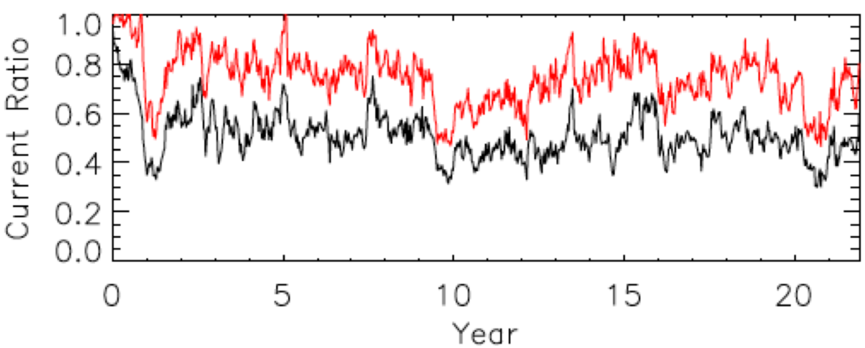
0.73 0.55 : 33%



0.65 0.46 : 41%



0.74 0.57 : 30 %



$$\Phi_s(t) = R_\odot^2 \int_s |B_r(R_\odot, \theta, \phi, t)| d\Omega,$$

$$E_m(t) = \int_V \frac{B^2(r, \theta, \phi, t)}{8\pi} d\tau,$$

$$J_V(t) = \int_V |j(r, \theta, \phi, t)| d\tau,$$

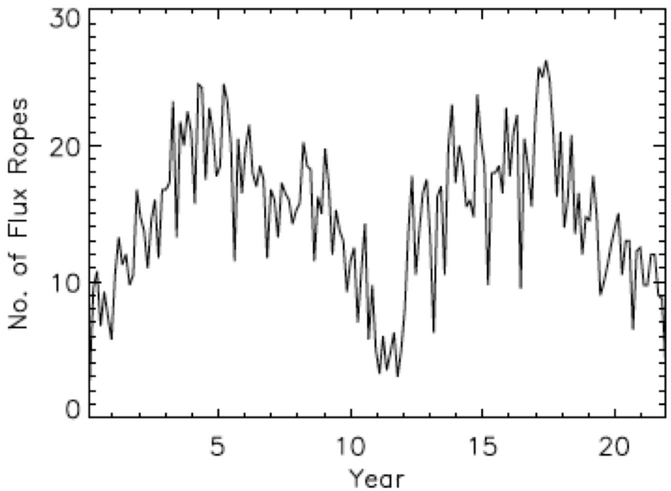
Red – L1 plus L5 FOV

Black – L1 only FOV

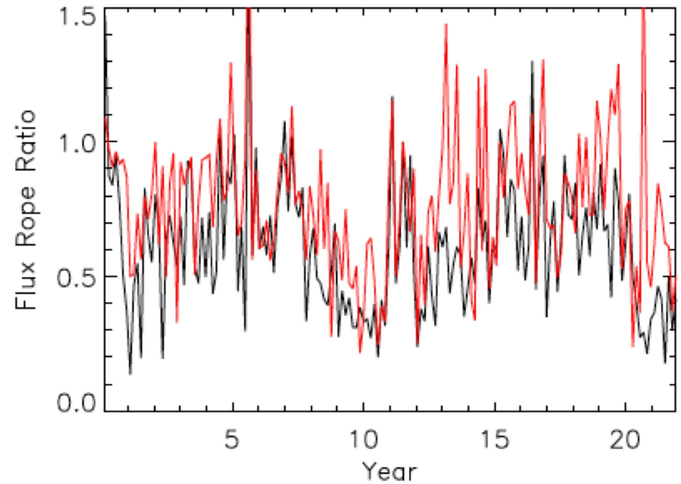
Blue - % improvement with L5

- Number of flux ropes

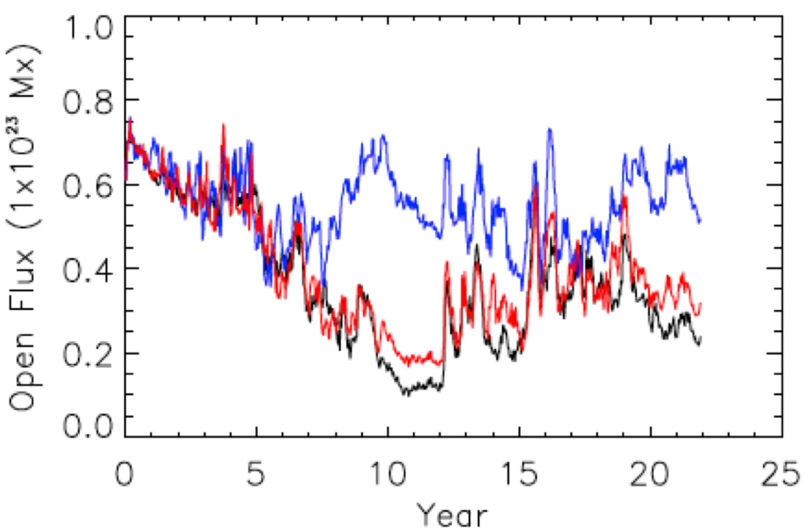
Reference Sun

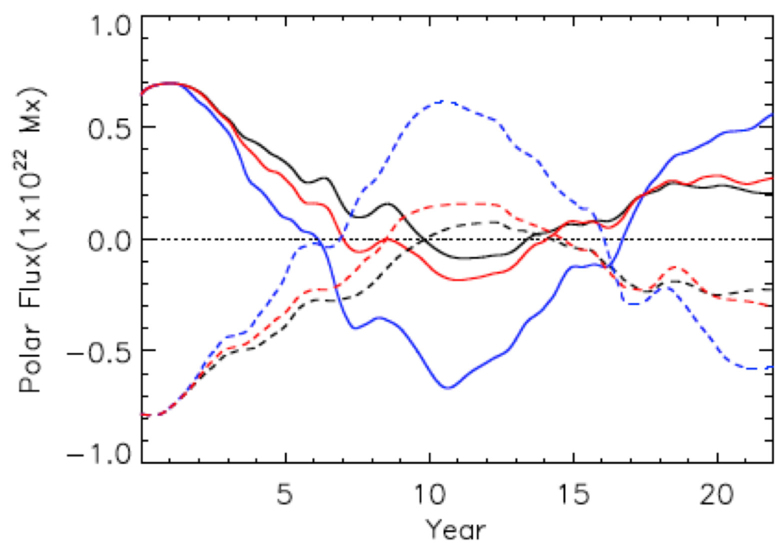


0.78 0.46 : 26%



- Open Flux: missed bipoles have severe consequence.





Summary

- Considered what improvements can be expected in the accuracy of global non-potential models if L5 magnetograph data exists.

- Used a reference sun simulation & two limited data simulations.

  Limited data: L1 only
  L1 & L5

- L1 & L5 simulation gives improvements of between 26-40% in global quantities dominated by low latitude contributions compared to Earth only.

- L1 & L5 attains an accuracy of 65-78% of reference global quantities (46-57% for Earth only).

- Full details given in published paper along with a comparison of other quantities and outline of future studies that are presently underway.

Mackay, Yeates and Bocquet (2016), APJ, V825

Still to Do

- Global Properties: Number of Ejected flux ropes.

- Local Properties: Correlation in free magnetic energy storage locations.
  Location and timing of flux rope ejections – in particular
  flux rope ejections between +/- 60^o of CM.