Babcock-Leighton solar dynamo models including the observed meridional circulation and surface flux loss

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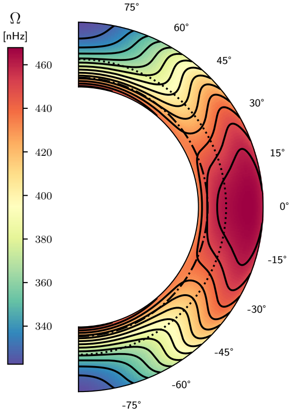
Open questions

Does the flux-transport dynamo using the observed meridional flow reproduce:

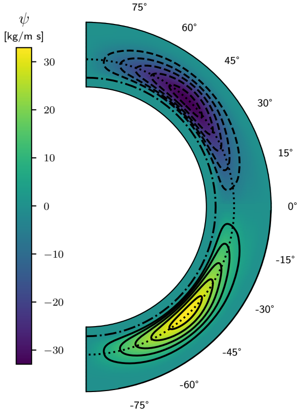
1. The 11 year cycle period
2. The equatorward propagation of sunspots
3. The emergence of sunspots within latitudes of $\pm \sim 40^\circ$ around the equator

Large-scale flows

MC from Gizon et al. 2020 averaged over cycles 23 and 24 and symmetrized across the equator



Belvedere et al. 2000



Gizon et al. 2020

Toroidal flux loss timescale

Cameron & Schüssler 2020:

Toroidal flux loss due to flux emergence has timescale $\sim$ 12 years

$\Rightarrow$removes most of the toroidal flux produced by the Ω-effect
$\Rightarrow$likely has a strong impact on the operation of the dynamo

Dynamo model equations

$$\frac{\partial A}{\partial t} = -\frac{(\boldsymbol{u}_\mathrm{p} + \boldsymbol{\gamma})}{r\sin\theta} \cdot \nabla(r\sin\theta A) + \eta\left(\nabla^2 - \frac{1}{r^2\sin\theta^2}\right)A + S$$

$$\begin{aligned}\frac{\partial B}{\partial t} = &- r\sin\theta(\boldsymbol{u}_\mathrm{p} + \boldsymbol{\gamma}) \cdot \nabla\left(\frac{B}{r\sin\theta}\right) + r\sin\theta(\nabla\times[A\hat{\boldsymbol{e}}_\phi])\cdot\nabla\Omega \\ &+ \eta\left(\nabla^2 - \frac{1}{r^2\sin\theta^2}\right)B - \frac{1}{r}\frac{\partial(rB)}{\partial r}\frac{\partial\eta}{\partial r} - B\nabla\cdot(\boldsymbol{u}_\mathrm{p} + \boldsymbol{\gamma}) - L\end{aligned}$$

Details in S. Cloutier, and R. H. Cameron, *A Babcock-Leighton dynamo model of the Sun incorporating toroidal flux loss and the helioseismically-inferred meridional flow*, to be submitted

Babcock-Leighton source and loss terms

From Leighton 1969 and Cameron & Schüssler 2020:

$$S(r,\theta,t) = f_S(r)N(n)\sin^n\theta\sin\delta\frac{R_\odot^{-1}b(\theta,t)}{\tau_0}$$

$$L(r,\theta,t) = f_L(r)N(n)\sin^n\theta\cos\delta\frac{B(r,\theta,t)}{\tau_0}$$

$$b(\theta,t) = \int_{0.7R_\odot}^{R_\odot} B(r,\theta,t)rdr$$

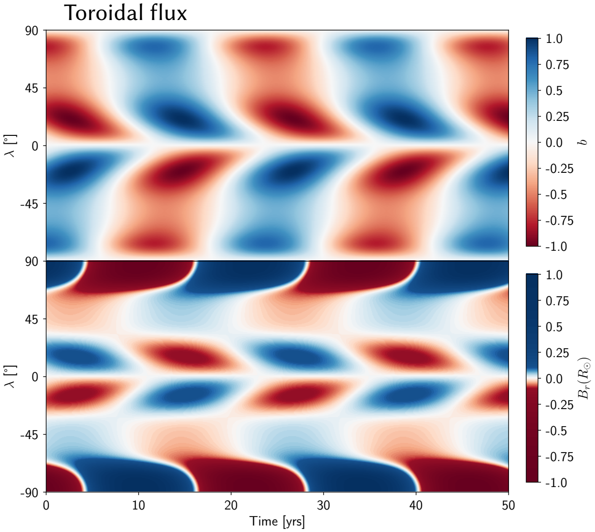
$$\sin\delta = \frac{1}{2}\cos\theta$$

$$n = 12, 1$$

See Karak & Cameron 2016 for source term with b

Strong evidence the dynamo could be located in the bulk of the CZ
(Wright & Drake 2016, Brown et al. 2010, Nelson et al. 2013, 2014, Cameron & Schüssler 2015, Schunker et al. 2020)

Results (n = 12 case - emergence latitudes constrained)



pumping depth:

$0.80\ R_\odot$

pumping velocity:

11.2 m/s

diffusivity:

30 km^2/s

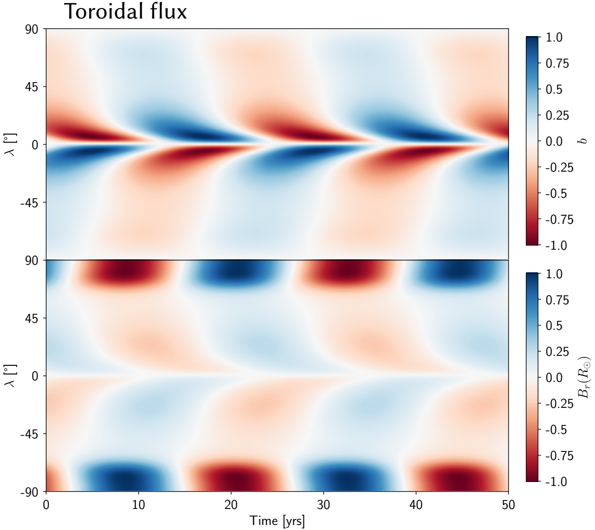
source/loss timescale:

τ_0 = 27.8 yrs

toroidal flux loss timescale:

τ_L = 24.0 yrs

Results (n = 1 case - emergence latitudes unconstrained)



pumping depth:

$0.80\ R_\odot$

pumping velocity:

17.7 m/s

diffusivity:

10 km^2/s

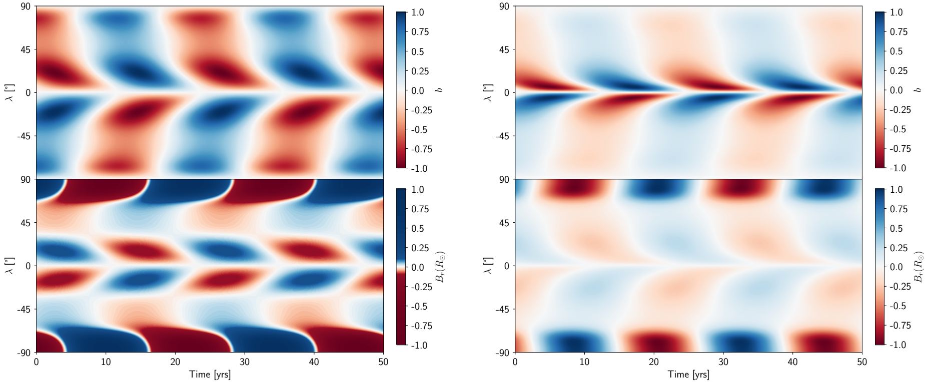
source/loss timescale:

τ_0 = 12.9 yrs

toroidal flux loss timescale:

τ_L = 17.5 yrs

$n = 12$ $n = 1$



90
45
0
-45
-90
0
10
20
30
40
50
Time [yrs]
λ [°]
1.0
0.75
0.5
0.25
0.0
-0.25
-0.5
-0.75
-1.0
b
$B_r(R_\odot)$

Conclusion

Helioseismically-inferred meridional flow from Gizon et al. 2020 allows for relatively solar-like butterfly diagrams

Self-consistent toroidal flux loss can't be ignored

Deep pumping can explain why sunspots are confined to low latitudes

$\Longrightarrow$possibly solves the high polar field problem of FTD models

Pumping should store the toroidal flux below $\sim 0.8 R_\odot$

$\Longrightarrow$+ low diffusivities: MC likely has key role in setting the dynamo period