The effects of the surface inflows on quenching of solar cycles

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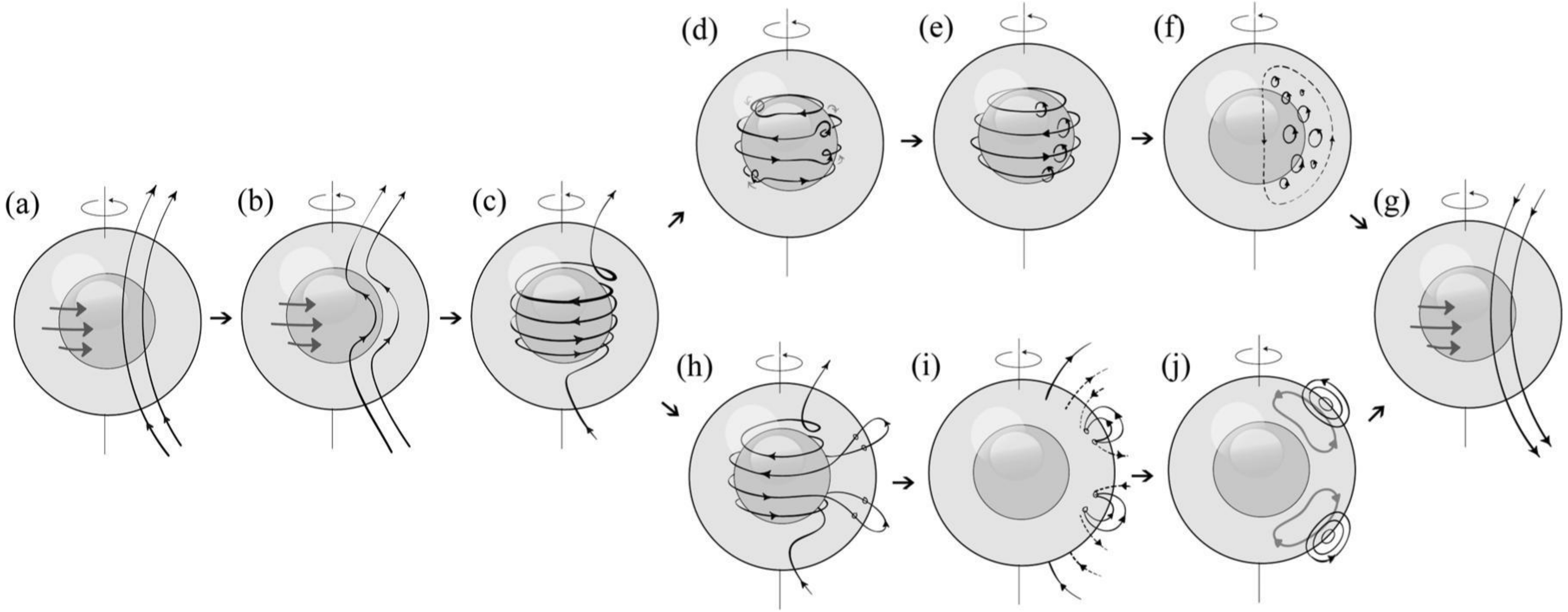
Introduction



Sanchez et. al. 2014, An. Acad. Bras. Ciênc. 86 (1), 11–26.

Motivations

- Understand the effects of surface inflows on the solar dynamo.
- Investigate the quenching parameters in Surface Flux Transport models (SFT).
- Explore the effects of surface inflows on the SFT’s in the presence of quenching mechanisms.

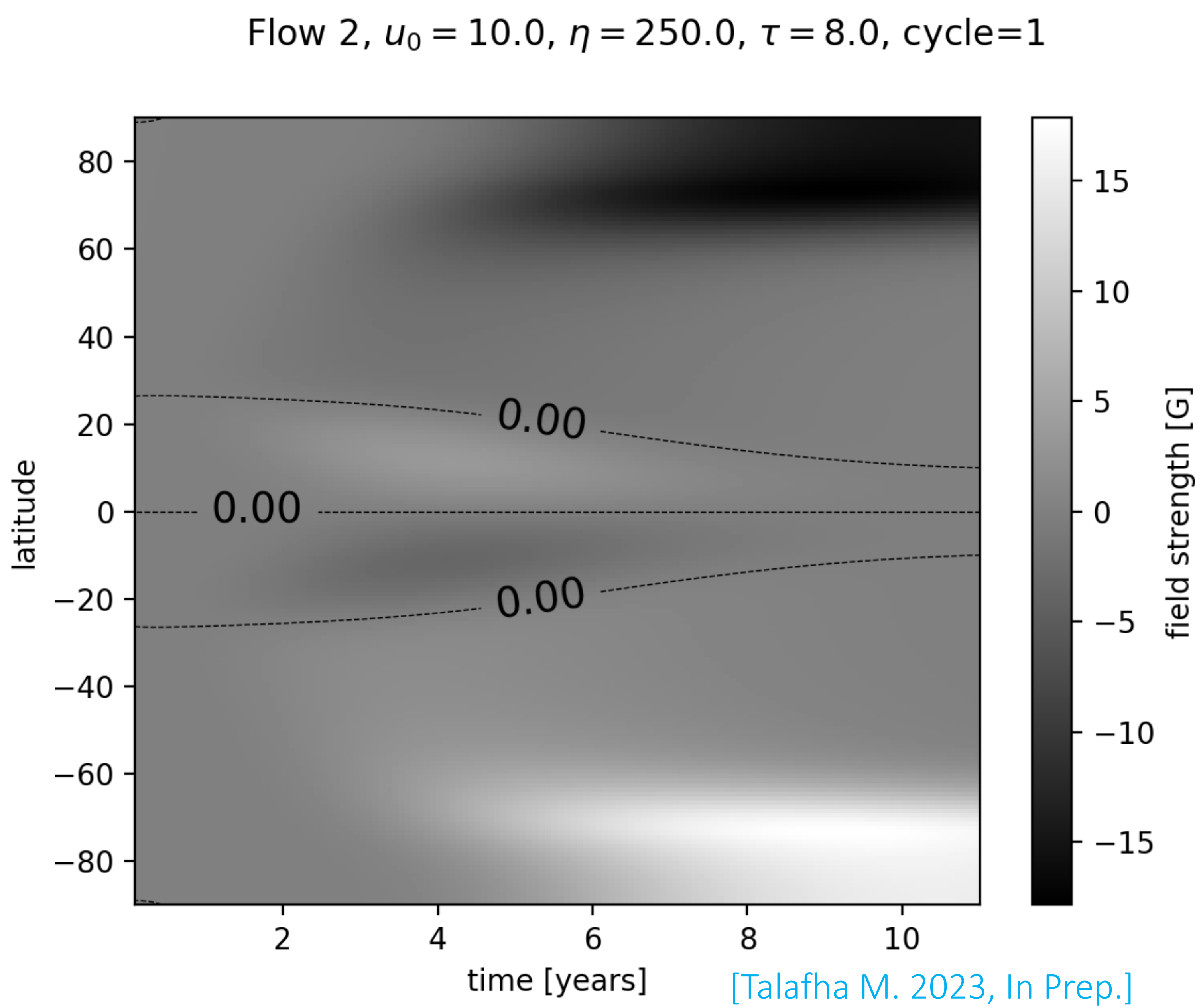
Surface Flux Transportation Model (SFT)

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

- considering the magnetic field to be predominantly radial on global scales solving only the r-component, after enforcing the null divergence condition throughout:

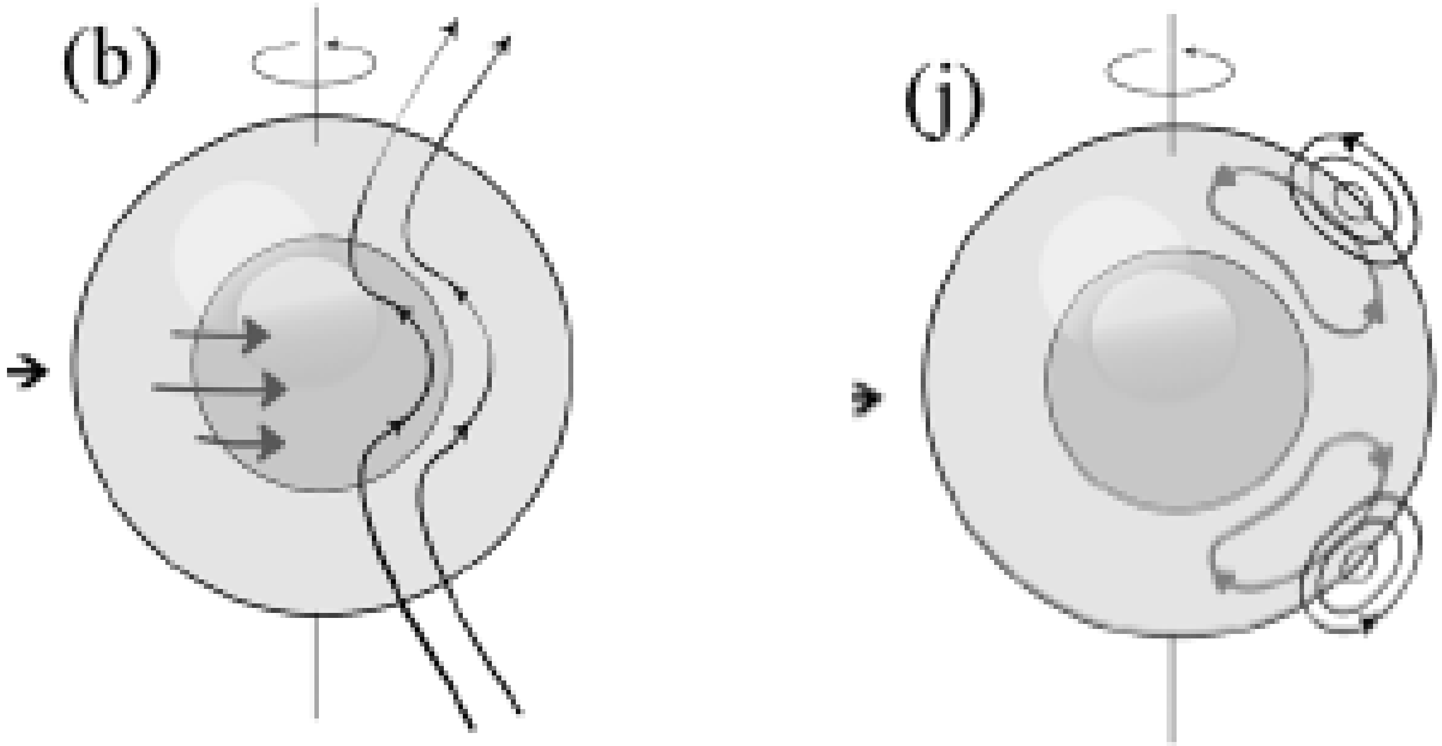
$$\frac{\partial B_R}{\partial t} = -\frac{1}{R\sin\theta}\frac{\partial}{\partial\theta}[u_\theta(R,\theta)B_R\sin\theta] - \Omega(R,\theta)\frac{\partial B_R}{\partial\varphi}$$

$$+\frac{\eta_R}{R^2}\left[\frac{1}{\sin\theta}\frac{\partial}{\partial\theta}\left(\sin\theta\frac{\partial B_R}{\partial\theta}\right) + \frac{1}{\sin^2\theta}\frac{\partial^2 B_R}{\partial\phi^2}\right] - \frac{B_R}{\tau_R} + S_{BMR}(\theta,\phi,t)$$



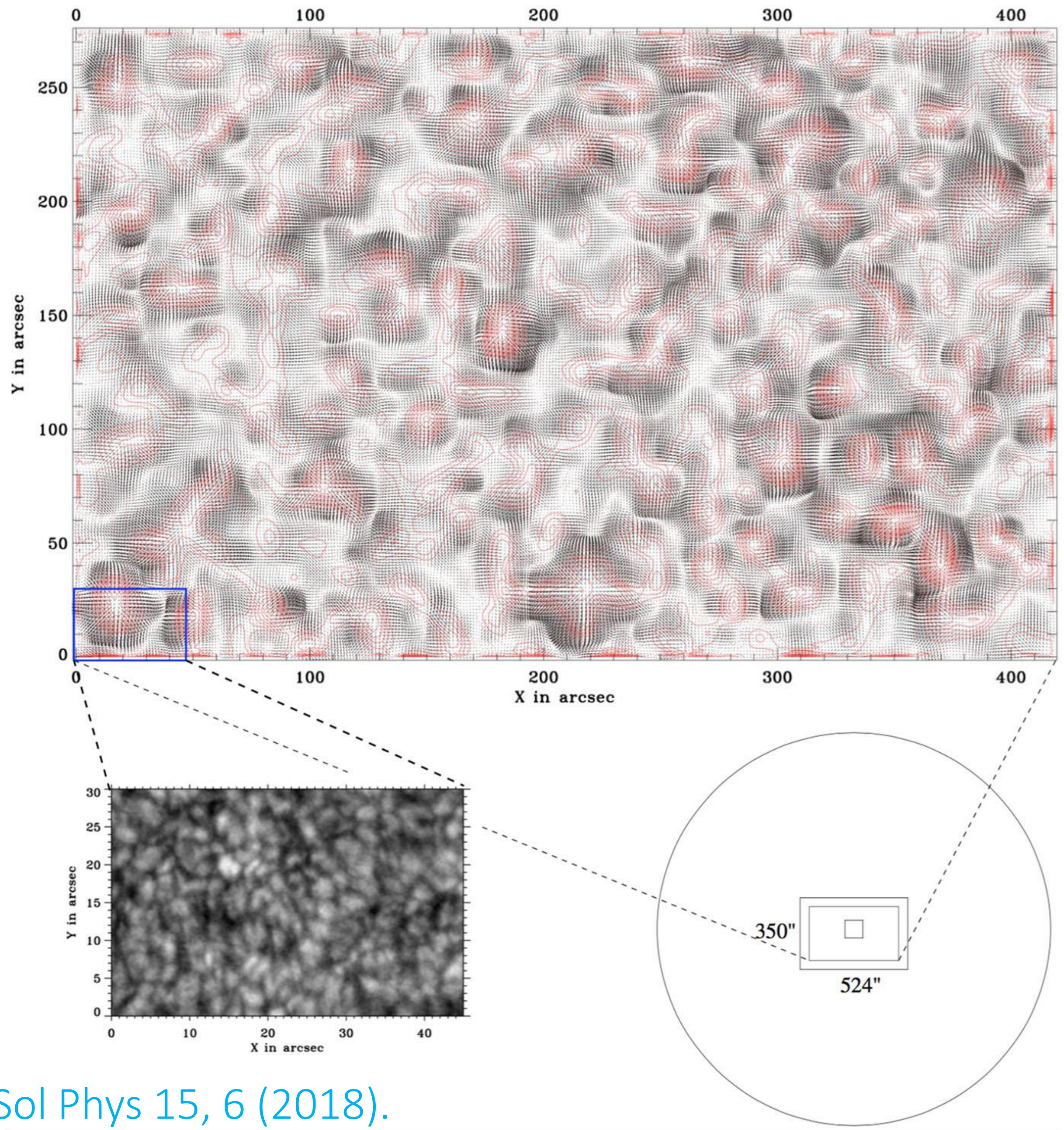
[Talafha M. 2023, In Prep.]

- Large scale flows: Differential rotation and Meridional flow



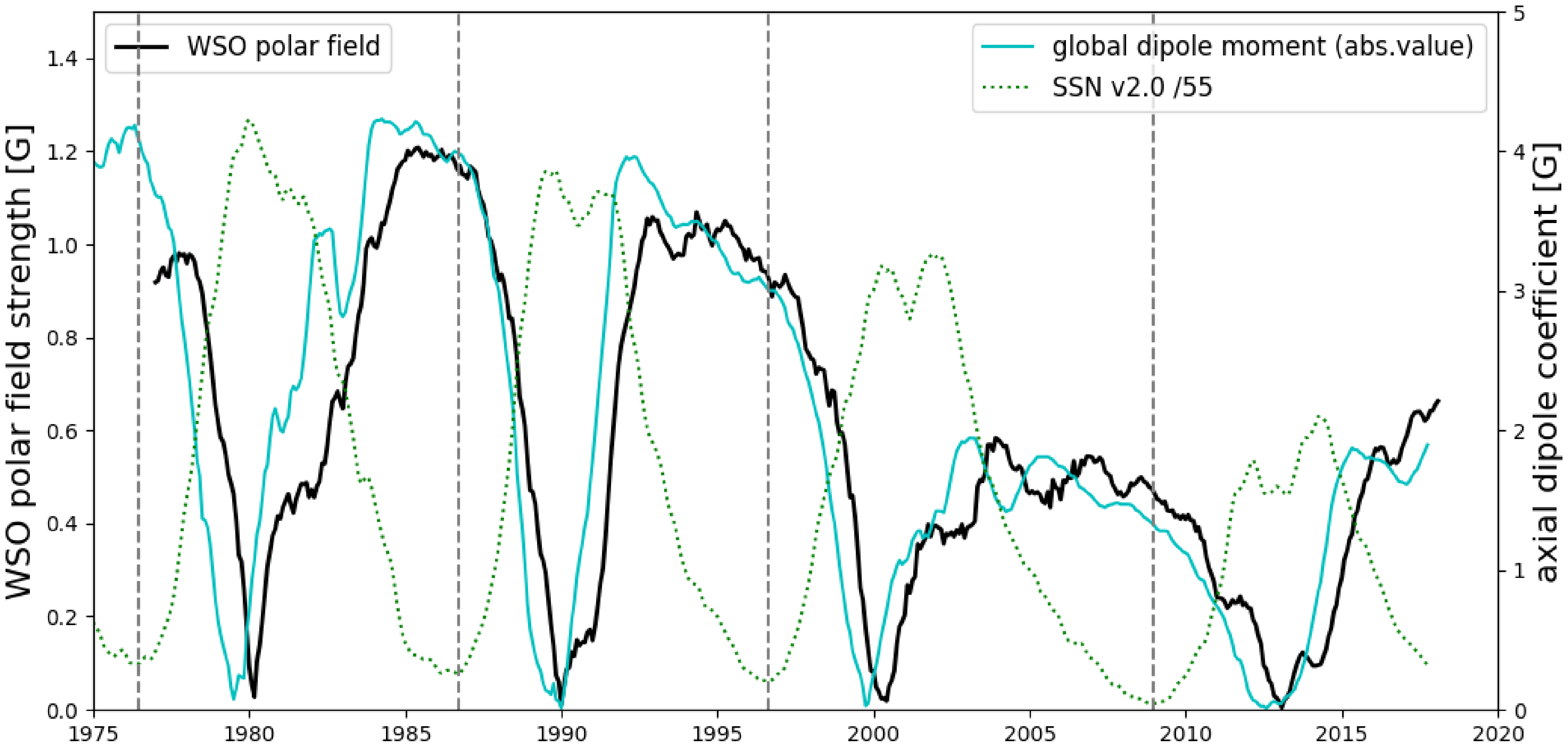
Sanchez et. al. 2014, An. Acad. Bras. Ciênc. 86 (1), 11–26.

- Small scale flows: diffusion



Rincon, F., Rieutord, M.. Living Rev Sol Phys 15, 6 (2018).

Constraints



Petrovay, K. & Talafha, M. 2019, A&A, 632, A87

Computations

- Python script include (FTCS scheme)

1- Source function: represented by a pair of rings of opposite magnetic polarity.

$$S(\lambda,t) = kA_m S_1(t) S_2(\lambda; \lambda_o(t) - \Delta\lambda(t), \delta\lambda)$$
$$- kA_m S_1(t) S_2(\lambda; \lambda_o(t) + \Delta\lambda(t), \delta\lambda)$$
$$+ kA_m S_1(t) S_2(\lambda; -\lambda_o(t) - \Delta\lambda(t), \delta\lambda)$$
$$- kA_m S_1(t) S_2(\lambda; -\lambda_o(t) + \Delta\lambda(t), \delta\lambda)$$

k : is a factor alternating between even and odd cycles.

A_m : is an arbitrary amplitude depending on the flow profile (0.015 for the sinusoidal case.)

$S_2(\lambda; \lambda_o(t), \delta\lambda)$ is the latitudinal profile represented by a Gaussian, migrating equatorward during the course of a cycle.

the time profile of solar activity in a typical cycle was determined by Hathaway et al. 1994, from the average of many cycles

Their trajectory during the course of a cycle is given by a quadratic fit from Jiang et al. 2011.

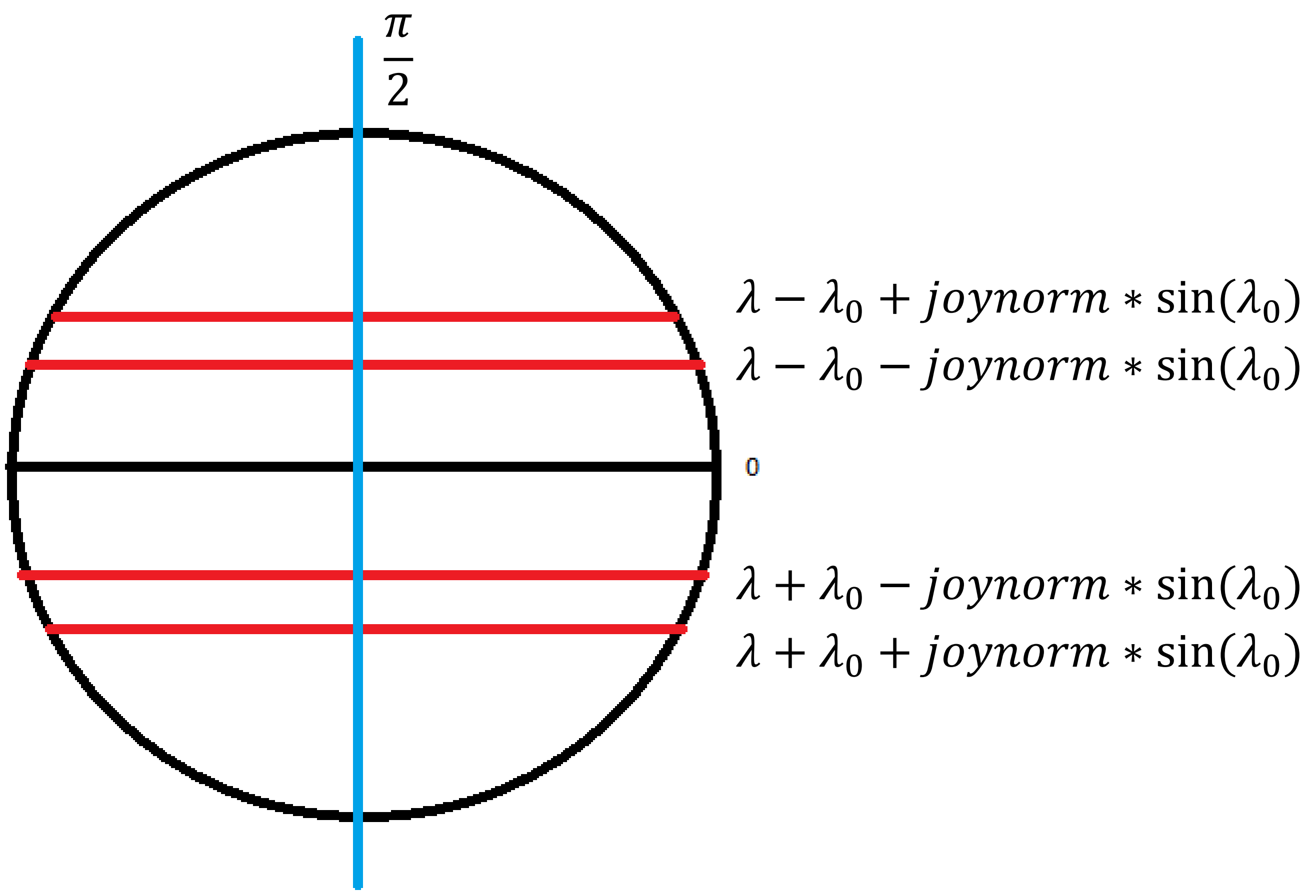
The latitudinal separation of the rings is a consequence of Joy's law.

$$\lambda_o[o] = 26.4 - \frac{34.2t}{P} + 16.1(\frac{t}{P})^2$$

$$2\Delta\lambda = 0.5\frac{\sin\lambda}{\sin 20^o}$$

$$S_1(t) = at_c^3/[\exp\left(\frac{t_c^2}{b^2}\right) - c]$$

Latitudes of pair of rings of opposite polarity



The latitudinal profile (S_2):

$$s_2(\lambda;\lambda_o,\delta\lambda) = \frac{\delta\lambda_o}{\delta\lambda}\exp\left[-\frac{(\lambda-\lambda_o)^2}{2\delta\lambda^2}\right]$$

$$\delta\lambda = \left[0.14 + 1.05\left(\frac{t}{P}\right) - 0.78\left(\frac{t}{P}\right)^2\right]\lambda_o$$

$$\delta\lambda_o = 6.26^o$$

[Jiang, et. al. 2011, A&A, 528, A82]

Meridional flow profiles :

- (Van Ballegooijen et al. 1998); used by (Jiang et al. 2014).

$$u_c = \begin{cases} u_o \sin(\pi \times \lambda/90), & if\ |\lambda| < \lambda_o \\ 0 & , otherwise \end{cases}$$

- Based on the optimized parameters [Petrovay, K. & Talafha, M. 2019]
  - **Diffusivity:** values (η) (250 and 600) $km^2 s^{-1}$.
  - **Source decay time:** values (τ) (8 - 100) yr.
  - **Meridional flow velocity:** values (u_o) (11) ms^{-1}.

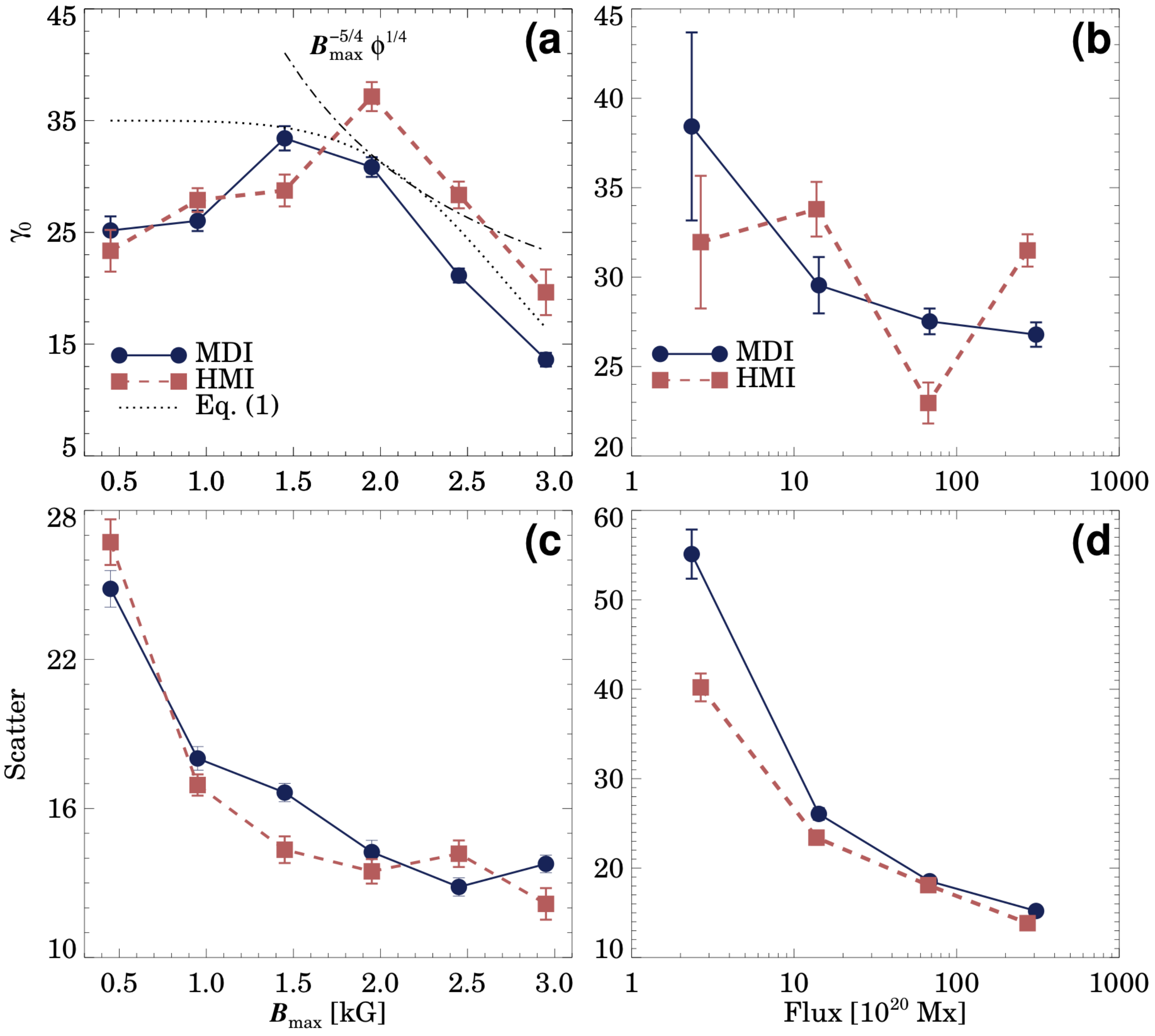
Parameter	NoQ	Different cases of LQ and TQ				
b_{lat}	0	1.5	2.4*	3.5	4.5	5.5
b_{joy}	0	0.05	0.1	0.15*	0.2	0.25

* standard values [Jiang, et. al. 2011, A&A, 528, A82]

- For each combination of the parameters, we run the code solving SFT equation for 1000 solar cycles to produce a statistically meaningful sample of cycles.

Nonlinearities in solar cycles

- Tilt quenching (TQ)

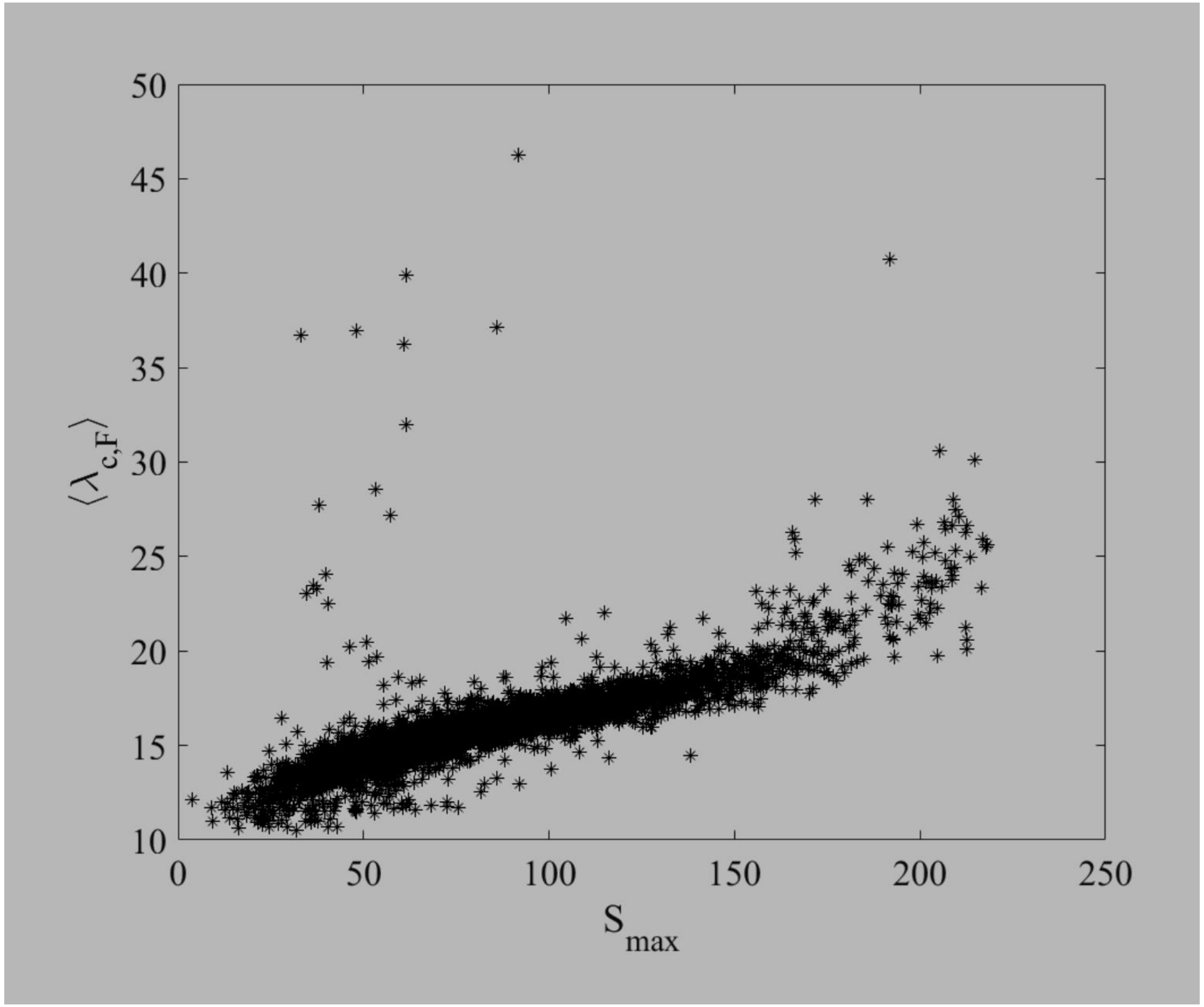


Jha, B. K., Karak, B. B., Mandal, S., & Banerjee, D. (2020. The Astrophysical Journal Letters, 889(1), L19.

Nonlinearities in solar cycles

- Latitude quenching (LQ)

  - A positive correlation between the cycle amplitude and average emergence latitude of active regions



[Talafha, et. al. 2022, A&A, 660, A92]

Tilt quenching (TQ)

$$\Delta\lambda = 1.5^o sin\lambda_o \left(1 - b_{joy}\frac{A_n - A_0}{A_0}\right)$$

[Talafha, et. al. 2022, A&A, 660, A92]

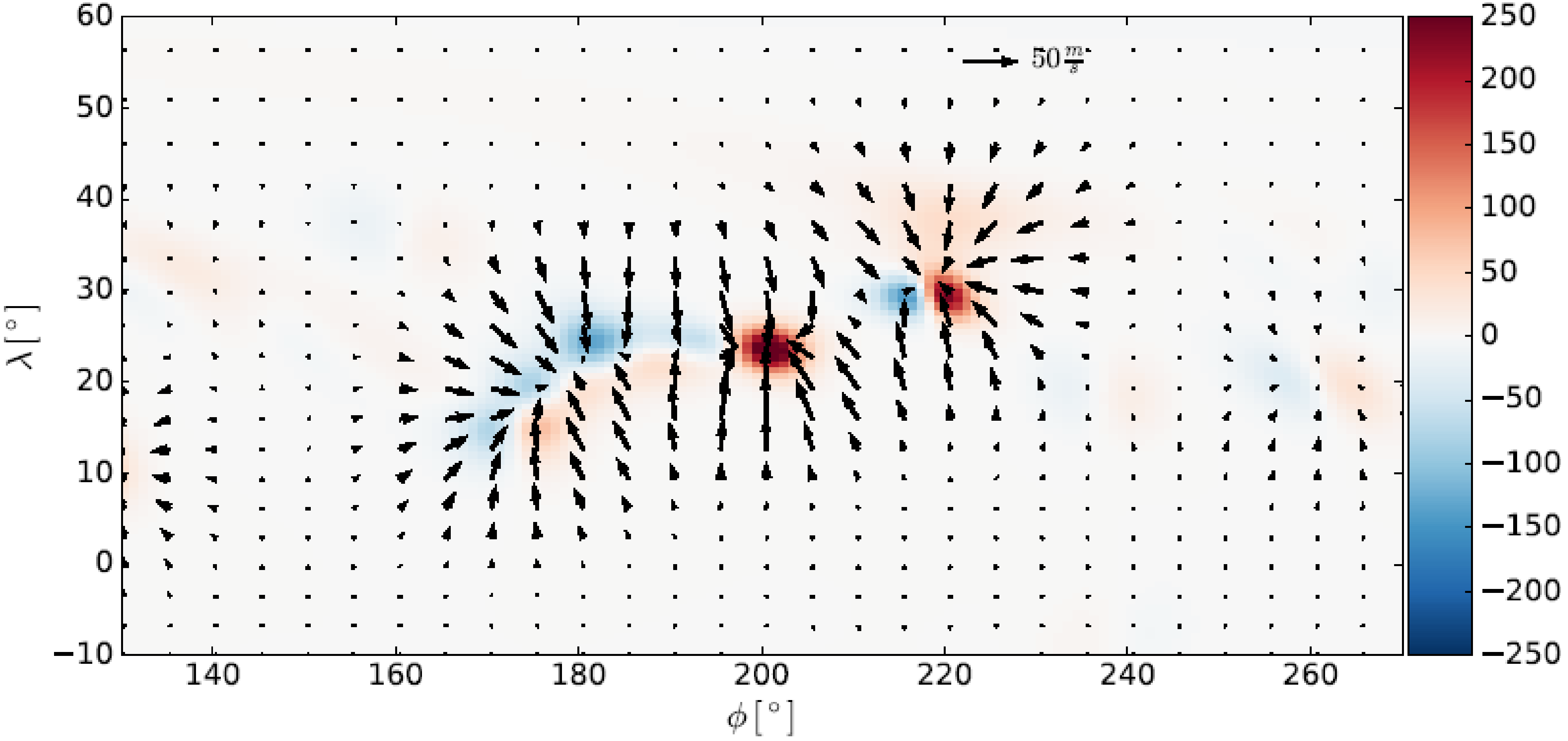
Latitude quenching (LQ)

$$\lambda_o(t;i) = \left[26.4 - 34.2\left(\frac{t}{P}\right) + 16.1\left(\frac{t}{P}\right)^2\right]\left(\frac{\lambda_i}{14.6^o}\right)$$

$$\lambda_i = 14.6^o + b_{lat}\frac{A_n - A_0}{A_0}$$

[Jiang, et. al. 2011, A&A, 528, A82]

Surface inflows



Martin-Belda, D., & Cameron, R. H. (2017). A&A, 597, A21.

$$u_c = A \times \begin{cases} u_o \sin(\pi \times \lambda/\lambda_o) + \Delta v(\lambda, t), & if\ |\lambda| < \lambda_o \\ 0 & , otherwise \end{cases}$$

$$\Delta v(\lambda, t) = \begin{cases} v_o \sin(\lambda - \lambda_c/\Delta\lambda_v), & -180 < [\lambda - \lambda_c/\Delta\lambda_v] < 180 \\ 0 & , otherwise \end{cases}$$

[Jiang et. al. 2010. The Astrophysical Journal 717(1), 597]

Where:

$\lambda_o = 75^o$

$\Delta\lambda_v = 15^o$

$v_o = 0\ and\ 5\ m/s$

$\lambda_c = 0, \pm 5, \pm 15, \pm 25$

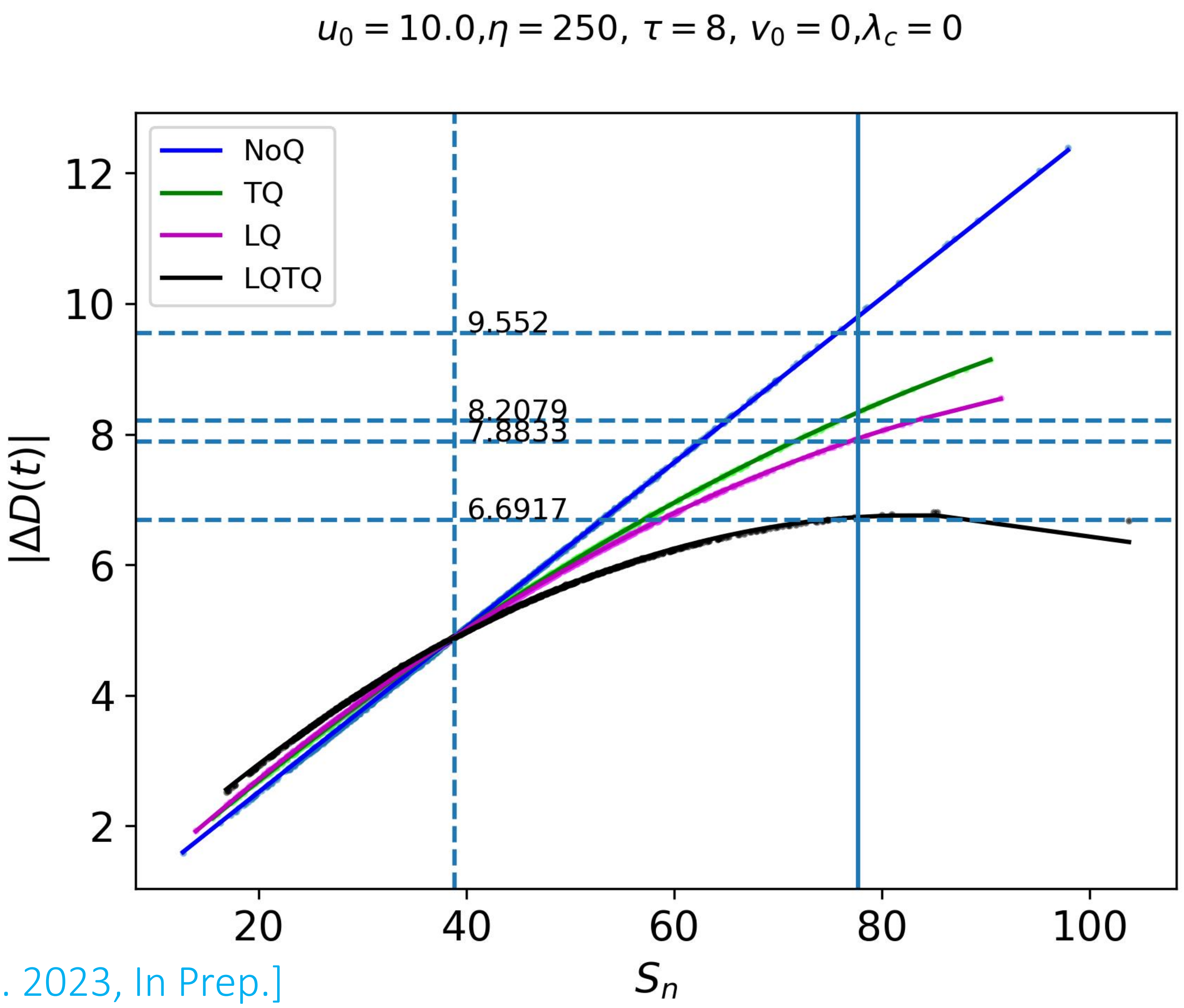
- The amplitude of the perturbed meridional flow (A) was scaled to be depending on the cycle amplitude as ($[A_n\text{-}A_0]/A_0$)
- A_0 is an arbitrary reference value corresponding to a “typical” or average cycle amplitude.

Preliminary Results

- A linear dependence of both quenching parameters (b_{joy} and b_{lat}) on the dipole moment of the solar cycle.

- The build up of the surface inflows in the cases of λ_c= ±5 and ± 25 was very quick, it covered the entire surface by the first 20 solar cycles.

- Net contribution of a solar dipolar moment vs. cycle amplitude for the linear case and for the cases with tilt quenching and/or latitude quenching with quadratic fits. Parameter values were u_0 =10m/s, $\eta = 250\text{km}^2$ /s, and $\tau = 8$ years.
- No Inflow considered



[Talafha M. 2023, In Prep.]

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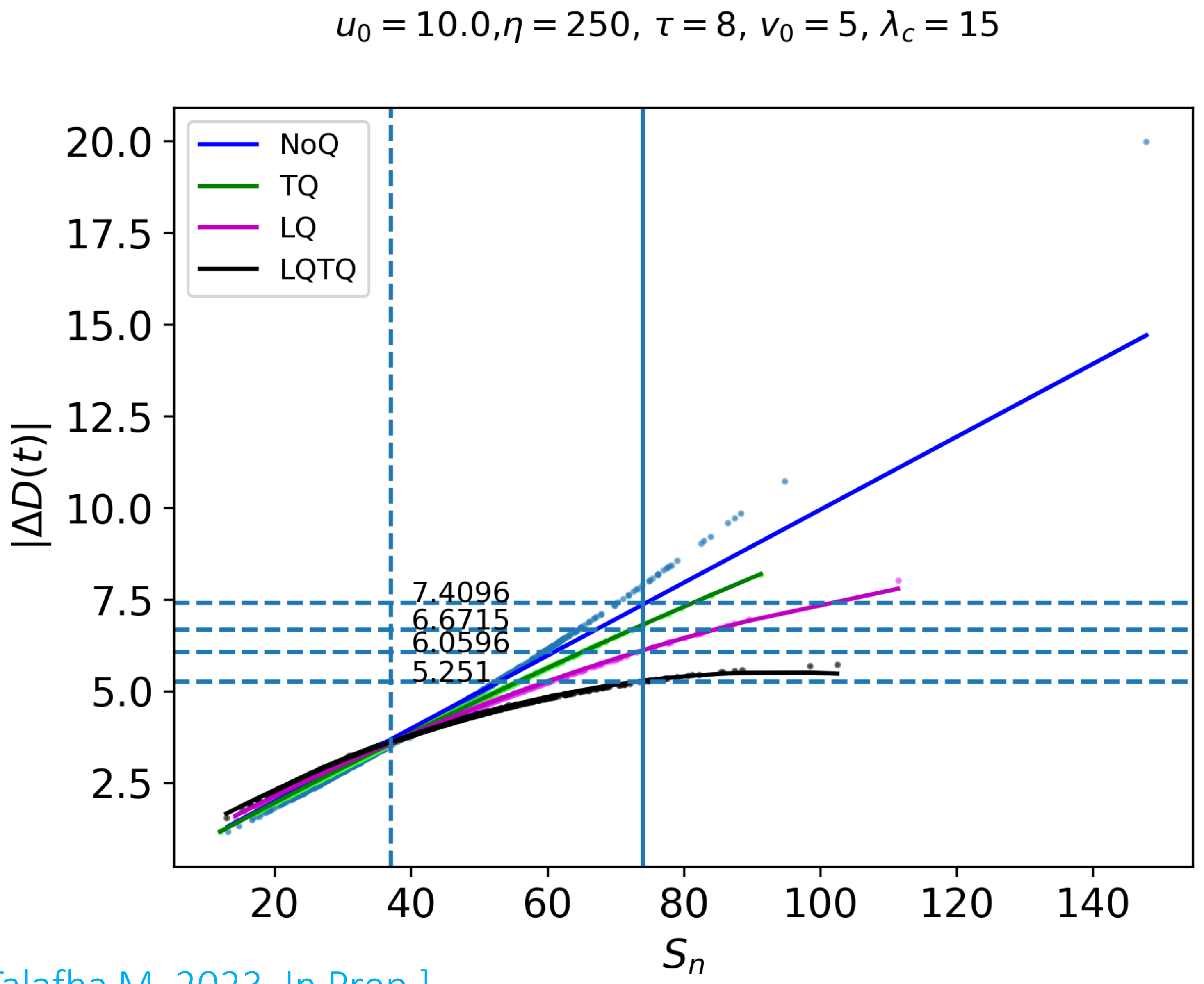
- Inflow considered with $v_0 = 5$ and $\lambda_c = 15$



[Talafha M. 2023, In Prep.]

- **Introducing surface inflows to the model produce lower net contribution value of solar dipolar moment** -- In Agreement with the 2x2D dynamo model [Nagy, M. et. al.(2020). JSWSC, 10, 62.]

Difference between the no inflow case and the case with inflow v0 = 5 and λc = ±15 in deviations of the nonlinear models |ΔDn| from the linear case measured at a certain SSN value for u0 = 10 m/s.

η [km^2/s]	τ [yr]	Δdev_{LQTQ}	Δdev_{LQ}	Δdev_{TQ}	Δdev_{NoQ}
250	8	1.4407	1.8237	1.5364	2.1424
250	∞	1.7566	2.1436	1.8074	2.1273
600	8	1.2398	1.3772	1.7802	2.2745
600	∞	1.5271	1.4997	2.0958	1.9429

[Talafha M. 2023, In Prep.]

Acknowledgements

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Thank you

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