The Effect of Magnetic Variability on Angular Momentum Loss for the Sun

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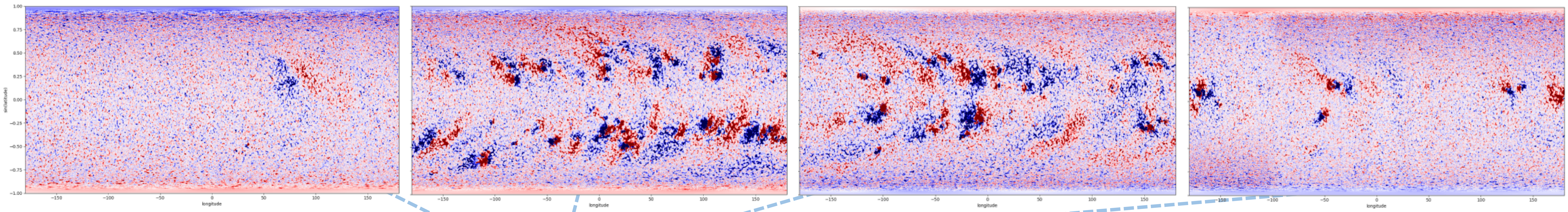
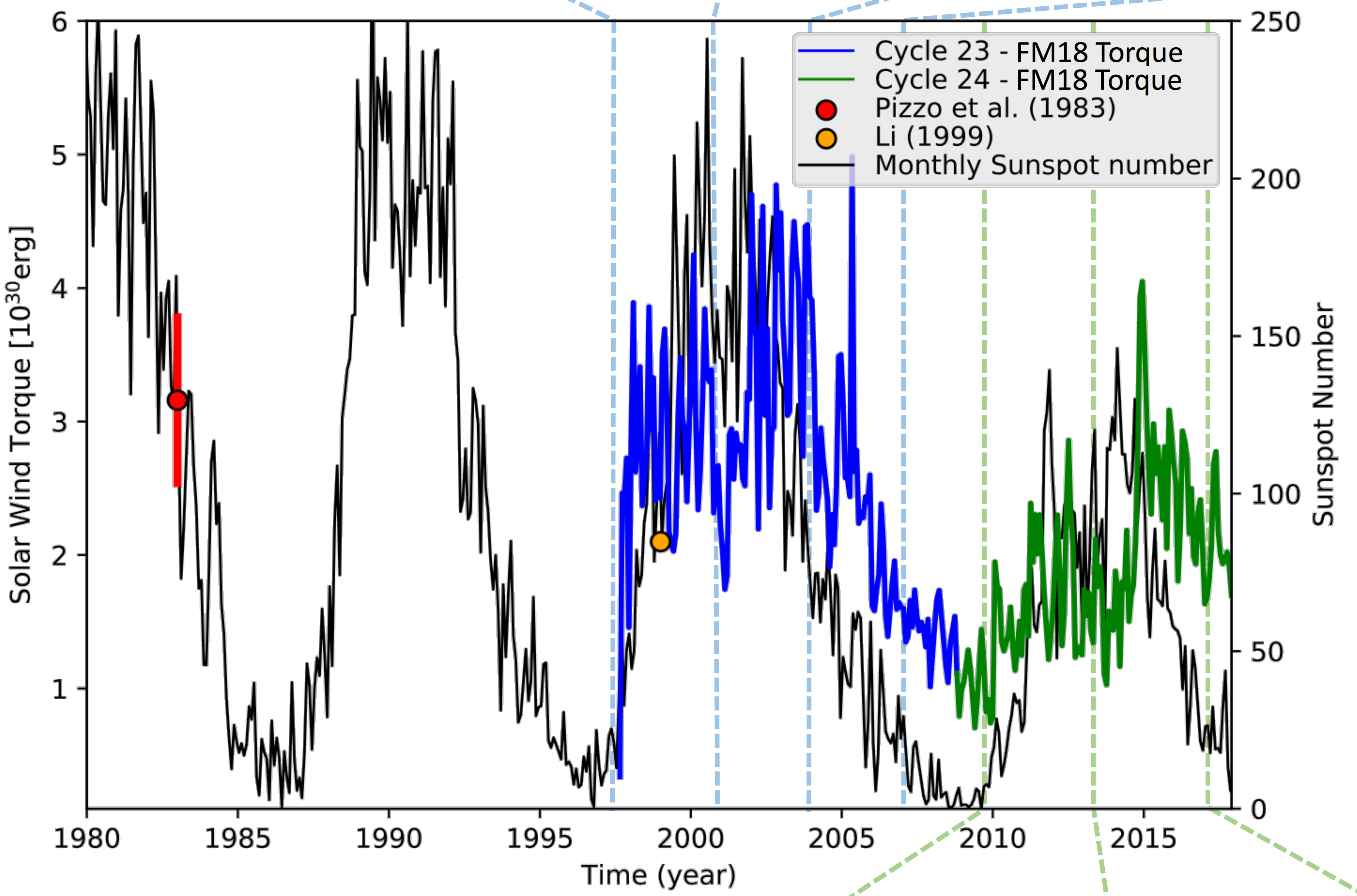
Finley, Matt & See. (2018, Submitted)





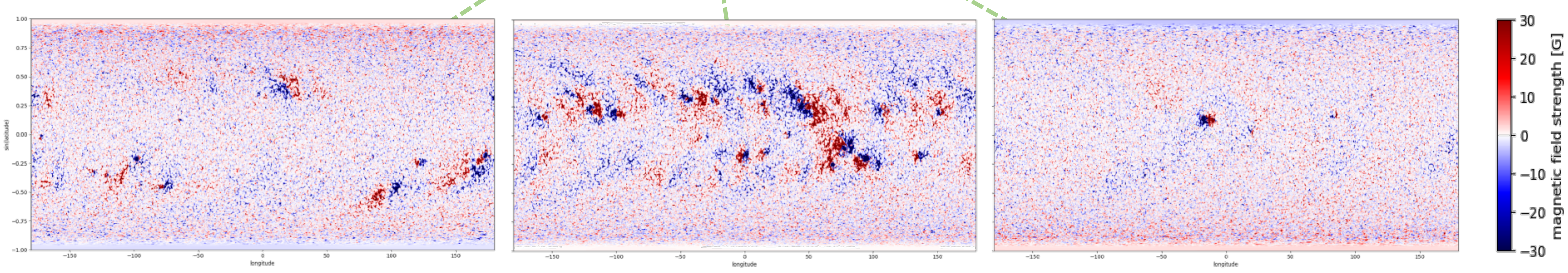
1.Summary

- Cool stars spin-down during their main sequence due to stellar winds.
- The Sun is no different, it has an average rotation period of ~27 days, and continues to shed mass in the solar wind at a around ~1×10^{12}g/s.
- Here we calculate the angular momentum loss rate during the solar cycle to examine the role of magnetic variability.
- We have applied the torque formulation of **Finley & Matt (2018)** to the wealth of solar data available from in-situ spacecraft (Section 2), and compare this to the inferred torque based on the observed spins of other stars (Section 3).
- Our current estimate for the solar torque is a factor ~ 3 smaller than required by current rotational evolution models.

Magnetograms:
- SOHO/MDI
- SDO/HMI

Solar Wind Data:
- ACE/SWOOPS+MAG

Sunspot Number:
- WDC-SILSO



2.Solar Torque Predicted from Open Magnetic Flux Measurements

The semi-analytic result from **Finley & Matt (2018)**, which continues work from **Réville et al. (2015)** and **Pantolmos & Matt (2017)**, allows for the calculation of the angular momentum loss based on the open magnetic flux, and mass loss rate,

$$\phi_{open} = \oint_A |\mathbf{B}\cdot\mathbf{dA}|, \qquad \dot{M} = \int_A \rho\mathbf{v}\cdot\mathbf{dA},$$

where the stellar wind magnetic field, mass density, velocity are **B**, $\boldsymbol{\rho}$, and **v** respectively**,** and **A** is a closed surface which is outside the last closed magnetic field loop.

The expression derived for the angular momentum loss rate is given as (cgs),

$$\tau_* = 0.101\dot{M}\Omega_* R_*^2\left(\frac{\phi_{open}^2/R_*^2}{\dot{M}v_{esc}}\right)^{0.742},$$

which incorporates the stellar rotation rate, radius and escape velocity (Ω_*, R_*, v_{esc}). For solar parameters this produces a simple relationship for the solar wind torque,

$$\tau_\odot[\mathrm{erg}] = 2.14\times10^{-7}(\dot{M}[\mathrm{g/s}])^{0.26}(\phi_{open}[\mathrm{Mx}])^{1.48}$$

Estimating the open magnetic flux and mass loss rate in the solar wind using the Advanced Composition Explorer (ACE) spacecraft, we produce an estimate for the solar wind torque, shown in the above Figure. The average value from the 22 years of observations is $\langle\tau_\odot\rangle = 2.3\times10^{30}\mathrm{erg}$. Previous estimates for the solar wind torque are also shown **(Pizzo et al. 1983, Li. 1999).** The angular momentum loss rate appears lower for cycle 24 than the previous cycle.

3.Solar Torque Inferred from Observed Stellar Rotation Rates

At the start of the main sequence, stars like the Sun exhibit a large range of rotation rates. This range is observed to converge towards a narrow distribution by the age of a few hundred Myrs (e.g. **Bouvier et al. 2014**). This asymptotic behaviour of observed spin rates gives us an independent constraint on the external torques, without any knowledge of the physics of stellar winds.

To derive a constraint on the torque, we approximate the torque to depend on rotation rate as a power law (**Schatzmann. 1962, Durney. 1972, Kawaler. 1988**),

$$\tau = \tau_\odot\left(\frac{\Omega}{\Omega_\odot}\right)^{p+1},$$

where $\tau_\odot$ is the long-time average value of the torque, and *p=2* is constrained by observations.

Assuming the moment of inertia is constant on the main sequence, and stars rotate as solid bodies, we integrate the angular momentum equation analytically,

$$\frac{\Omega}{\Omega_\odot} = \left(\frac{I_\odot\Omega_\odot}{p\tau_\odot t}\right)^{\frac{1}{p}}, \qquad \tau_\odot = 6.2\times10^{30}\ \mathrm{erg}\left(\frac{I_\odot}{6.90\times10^{53}\ \mathrm{g\ cm^2}}\right)\times\left(\frac{\Omega_\odot}{2.6\times10^{-6}\ \mathrm{rad/s}}\right)\left(\frac{4.55\ \mathrm{Gyr}}{t_\odot}\right)\left(\frac{2}{p}\right),$$

The value inferred from this method is 2.7 times greater than our average dynamical torque estimate. <u>The explanation for this discrepancy is not obvious, perhaps longer-time magnetic variability exists?</u>

References

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