Constraints on the Magnetic Morphology of Old Sun-like Stars

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Magnetic evolution of solar analogs

- Sample of solar analogs mapped with Zeeman Doppler Imaging (ZDI)
- Mean magnetic field strength decreases as rotation rate slows
- Fraction of magnetic energy in the poloidal component increases

Petit+2008
Weakened magnetic braking suspected

- Older Kepler field stars rotate more quickly than expected from theory.
- Discrepancy appears at critical Rossby number, $\text{Ro} = \left( \frac{P_{\text{rot}}}{\tau_c} \right) \sim \text{Ro}_\odot$
- Models with weakened magnetic braking beyond $\text{Ro}_\odot$ reproduce the data.
Weakened magnetic braking confirmed

- Distribution of rotation periods in the Kepler field shows long-period edge
- No detection bias: rotation from asteroseismology shows similar distribution
- Pile-up confirmed: sample with precise $T_{\text{eff}}$ shows range of ages near edge

van Saders+2019, Hall+2021, David+2022
To sustain a magnetic dynamo, the Rossby number cannot be too large!

$$\text{Ro} \equiv \frac{P_{\text{rot}}}{\tau_c}$$

Durney & Latour 1978, van Saders 2022, Kraft 1967
Activity level evolves continuously with age

- Activity of solar analogs and asteroseismic targets decline continuously
- Solar dipole field is \( \sim 1 \) G while unstructured quiet Sun has \( \langle B \rangle \sim 170 \) G
- Disruption of large-scale organization is irrelevant to integrated activity level
Variability is Sun-like before disappearing

- Variability in young solar analogs is multi-periodic, often appears irregular
- Sun-like cycles appear at high Rossby number, evolving to “flat activity”
- Grand minima could be intermittency as activity evolves across threshold

Egeland+2017, Tripathi+2021, Kitchatinov 2022
Cycles grow longer and weaker in old stars

• Stalled rotation coincides with longer activity cycles and weaker variability

• Same pattern observed in hotter and cooler stars at same Rossby number

• Position of 166620 above the lower sequence is an outlier similar to the Sun

Metcalfe & van Saders 2017
1. slow rotation becomes non-differential

Featherstone & Hindman 2016

2. loss of shear disrupts field conversion
3. decaying dipole stalls braking

Higgins 2012

Ω effect (poloidal → toroidal field)

Reville+2015
Evolutionary sequence: F-type stars

- **88 Leo**: detection of large-scale field, modeled by dipole with $B_d = 5.0$ G

- **$\rho$ CrB**: upper limits on field strength suggest a torque < 8% of 88 Leo

- Dominated by changes in field morphology, but ZDI needed for confirmation
Evolutionary sequence: solar analogs

$B_d = 1.34$ G
$B_q = 2.01$ G
$B_o = 0.86$ G

$0.373 \times 10^{30}$ erg

$B_d = 5.13$ G
$B_q = 2.88$ G
$B_o = 1.34$ G

$4.77 \times 10^{30}$ erg

Petit+2008, Boro Saikia+2020, Metcalfe+2022
HD 166620: grand minimum

- Showed a clear Sun-like activity cycle during the Mount Wilson survey
- Keck data are consistent in the late-90s, constant activity level after 2003
- Critical Rossby number corresponds to the mean activity level during cycles

$p_{\text{cyc}}=15.8 \text{ yr}, p_{\text{rot}}=42.4 \text{ d}$

Baum+2022, Luhn+2022
94 Aqr Aa: history of WMB

- Given stellar properties of subgiant, predict current rotation period \( (47 \pm 4 \text{ d}) \)

- Stalled magnetic braking beyond stellar middle-age yields: \( P_{\text{rot}} = 48 \pm 4 \text{ days} \)

- Standard spin-down for complete main-sequence yields: \( P_{\text{rot}} = 78 \pm 7 \text{ days} \)

\( P_{\text{cyc}} = 19.4 \text{ yr} \)

Metcalfe+2020
94 Aqr Aa: born-again dynamo

- Subgiant mass suggests that it was an F-type star on the main-sequence
- After losing any original cycle, rotation slowed as it expanded and cooled
- Convection zone became deeper, longer timescale reinvigorated the dynamo
• At a critical Rossby number comparable to the solar value, magnetic field loses large-scale organization
• At constant rotation period, the magnetic cycle grows longer and weaker on stellar evolutionary timescales
• As stars evolve below a critical activity level, cycles can become intermittent – producing grand minima
• Subgiant rotation slows further and cycles disappear, but then CZ deepens and reinvigorates the dynamo