Torus-Stable Zone Above Starspots

Xudong Sun (孙旭东)[1], Tibor Török[2], Marc DeRosa[3]

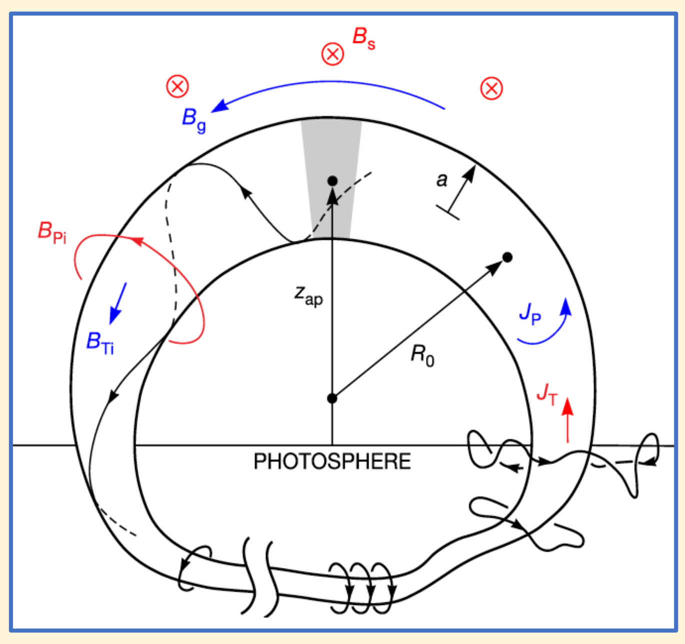
[1] University of Hawai'i (*xudongs@hawaii.edu*); [2] Predictive Science Inc.; [3] Lockheed Martin Solar & Astrophysics Lab

Detections of coronal mass ejections (CMEs) are rare on cool stars. Can the suppression of the "torus instability" by stellar magnetic fields explain this?

Torus Instability (TI) & Stellar Eruption

- TI: expansion instability of current-carrying magnetic flux tube is believed to drive many solar CMEs (Fig. 1)
- External field suppresses TI if the decay index n is below a critical value: $n = -\partial \ln B_s / \partial \ln h < n_c$ [e.g., Kliem & Török 2006]
- Large solar flares with no CME can occur even if TI is suppressed

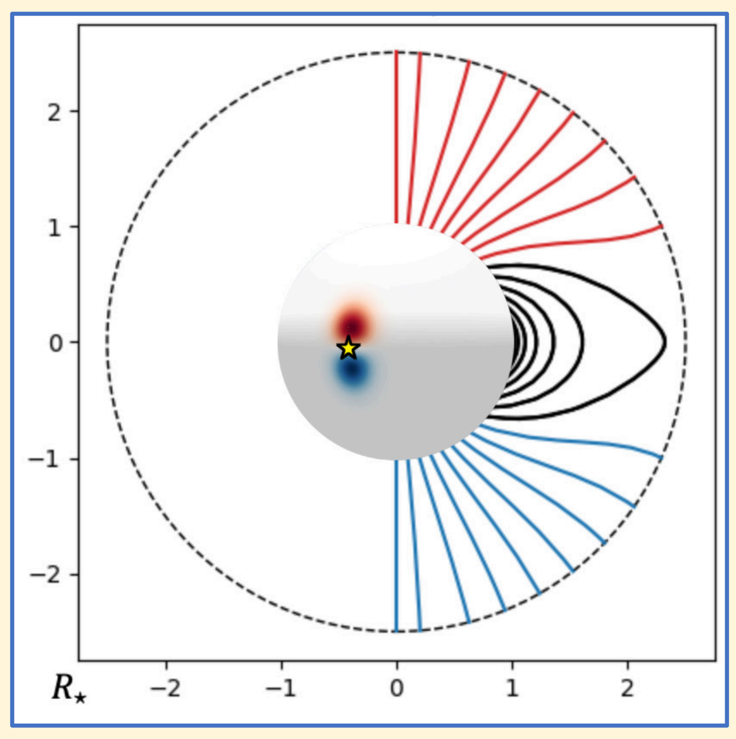
Fig 1 | Fields & currents in a toroidal flux rope. The foot points are anchored in the photosphere. The external field perpendicular to the rope B_s provides the strapping field that suppresses the TI. Adapted from Chen & Krall (2003).



Potential Field Source Surface (PFSS) Model

- We estimate the maximum height h_c of the "torus-stable zone" (where $n_c = 1.5$) using PFSS model (Fig.2) [Schrijver & DeRosa 2003]
- Bipolar magnetic region as starspot pair, modeled after a solar template: max field strength 2 kG; size a [Yeates 2020]
- Global dipole field with harmonic coefficient g_{10} is modulated by a source surface R_s where the field becomes radial and open

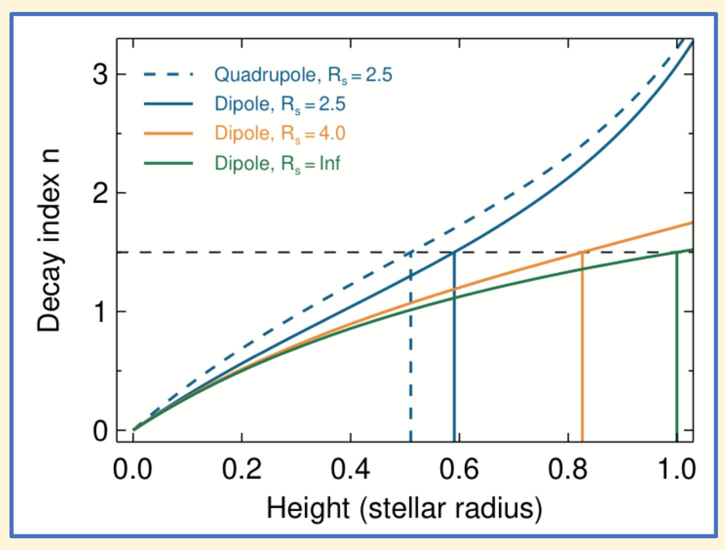
Fig 2 | PFSS model. The model contains a N-S oriented dipole and a bipolar region. The distance between the two flux centroids is $a = 20°$. The source surface radius is $R_s = 2.5R_\star$. The flux rope (not present) would be located between the starspots. The star shows where h_c is calculated.

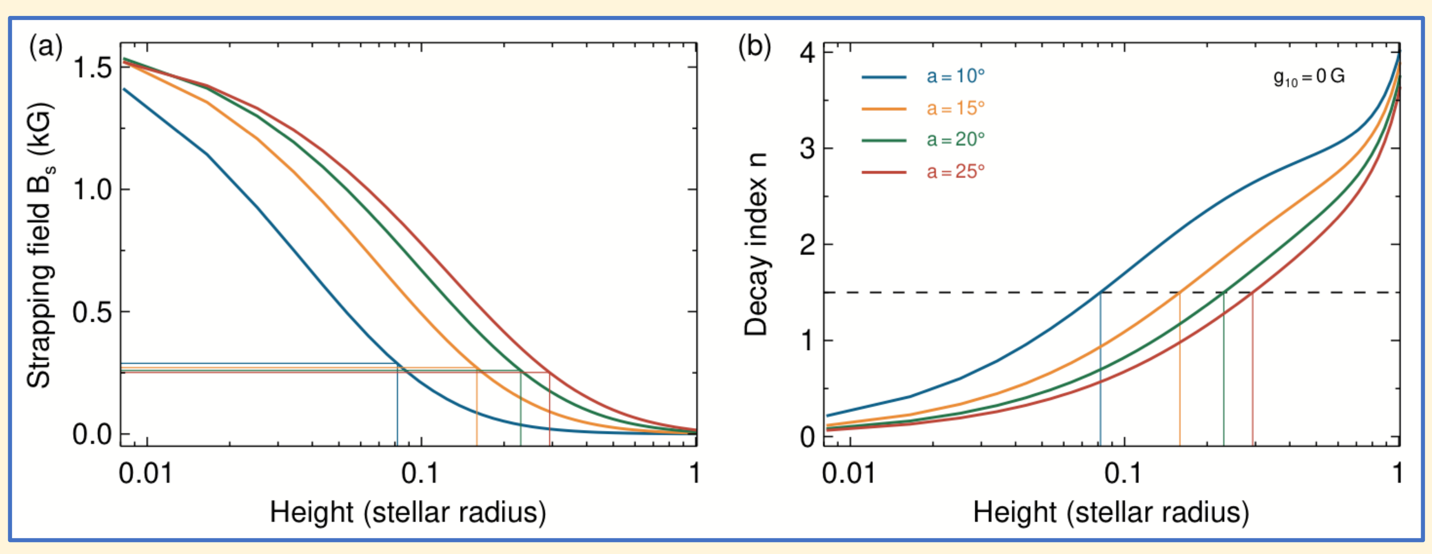


Interplay Between Starspots and Dipole

- *Dipole alone*: h_c is independent of g_{10}, $h_c = 0.59R_\star$ for default $R_s = 2.5R_\star$; $h_c \to R_\star$ when $R_s \to \infty$ (Fig. 3)
- *Starspots alone*: $h_c \approx 0.5aR_\star$ [c.f. Chen & Krall 2003]; large starspots ($a = 25°$) have $h_c = 0.29R_\star$ (Fig. 4)
- *Solar dipole* ($g_{10} < 10$ G): provides little confinement; for sunspots ($a < 10°$), $h_c < 0.08R_\star$ (Fig. 5a)
- *Moderate dipole* ($g_{10} = 200$ G): for large sunspots ($a = 10°$), h_c increases more than five times to over $0.45R_\star$ (Fig. 5b)
- *Strong dipole* ($g_{10} = 1000$ G): for large starspots ($a \geq 20°$), h_c increases by tens of percent and approaches upper limit (Fig. 5c)

Fig 3 | Decay index of dipole alone. Decay index $n(h)$ as a function of height $h = r - R_\star$. Three dipoles and a quadrupole with different R_s are considered. Vertical lines indicate the critical height h_c. Horizontal dashed line shows $n_c = 1.5$.





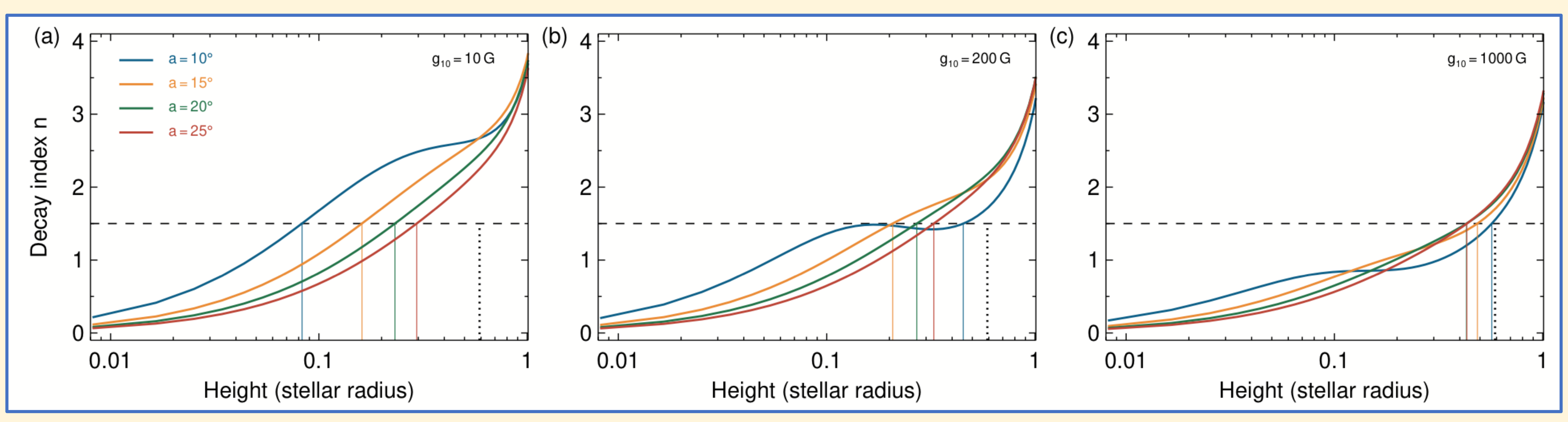


Fig 5 | Decay index of starspots plus dipole (left). Similar to Fig. 4b, but for three different g_{10}. Upper limit $h_c = 0.59R_\star$ is shown as vertical dotted line.

Fig 4 | Decay index of starspots alone (top). (a) Strapping field B_s as a function of h, for four different a and default R_s. Vertical lines show h_c. (b) Similar to Fig. 3.

Summary & Discussion

- For active cool stars, larger starspots [Berdyugina 2005], stronger dipoles [Donati & Landstreet 2009], and higher R_s [Schrijver et al. 2003] will all expand the TI-stable zone
- Pre-eruptive solar magnetic flux ropes are relatively "flat": $a < 0.5aR_\star < h_c$ [Cheng et al. 2020]. A large TI-stable zone (larger h_c) makes TI onset on cool stars more difficult
- TI suppression may contribute to the lack of stellar CME detection [Moschou et al. 2019]

Reference

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