Dynamics of Solar and Stellar Convection Zones and Atmospheres
Proceedings IAU Symposium No. 365, 2023
A. Getling & L. Kitchatinov, eds.
doi:10.1017/xxxxx

Exploring the Quenching of Bipolar Magnetic Region Tilts using AutoTAB

Bibhuti Kumar Jha[1], **Anu B. Sreedevi**[2], **Bidya Binay Karak**[2] **and Dipankar Banerjee**[3]

[1] Southwest Research Institute, Boulder 80302, USA
email:maitraibibhu@gmail,com
[2]Department of Physics, Indian Institute of Technology (Banaras Hindu University), Varanasi 221005, India
[3]Aryabhatta Research Institute of Observational Sciences, Nainital 263002, Uttarakhand, India

Abstract. The tilt of the bipolar magnetic region (BMR) is crucial in the Babcock–Leighton process for the generation of the poloidal magnetic field in the Sun. We extend the work of Jha et al. (2020) and analyze the recently reported tracked BMR catalogue based on AutoTAB (Sreedevi et al. 2023) from Michelson Doppler Imager (1996–2011) and Helioseismic and Magnetic Imager (2010–2018). Using the tracked information of BMRs based on AutoTAB, we confirm that the distribution of B_{max} reported by Jha et al. (2020) is not because of the BMRs are picked multiple times at the different phases of their evolution instead it is also present if we consider each BMRs only once. Moreover, we find that the slope of Joy's law ($\langle\gamma_0\rangle$) initially increases slowly with the increase of B_{max}. However, when $B_{\mathrm{max}} > 2.5$ kG, γ_0 decreases. The decrease of observed γ_0 with B_{max} provides a hint to a nonlinear tilt quenching in the Babcock–Leighton process.

Keywords. Sun, Bipolar Magnetic Regions, Solar Dynamo

---

1. Introduction

The Sun and solar cycle variability have intrigued curious minds for over a century. Despite being enriched by continuous observations over the past century, solar cycle variability remains a primary puzzle in solar physics. However, it is now well established that the solar activity cycle is driven by the solar dynamo process, operating in the interior of the Sun, and it is responsible for the observed cyclic behavior of the Sun (Charbonneau 2014; Karak et al. 2014a). Solar differential rotation (Jha et al. 2021; Jha 2022) amplifies the magnetic field by twisting and stretching the existing polar field at the beginning of the solar cycle. These amplified and buoyant magnetic fields rise through the convection zone, where they experience the Coriolis force and emerge at the photosphere as tilted bipolar magnetic regions (BMRs). The residual flux from these BMRs migrates toward the poles and leads to the cancellation of existing opposite-polarity flux, initiating the onset of new flux buildup at the poles. These new opposite-polarity flux components act as the seed field for the following cycle and dictate its strength. The process of reversal and the buildup of new magnetic fields through the residual field carried to the poles by meridional flows is known as the Babcock-Leighton process (Babcock 1959, 1961) .

One of the requirements for kinematic dynamo models, such as the Babcock-Leighton model, is the need for a nonlinear mechanism to suppress the exponential growth of the magnetic field (Charbonneau 2014). Flux loss due to magnetic buoyancy through the formation of BMRs (Biswas et al. 2022), latitude quenching (Karak 2020), and the tilt quenching are the three potential nonlinearities identified in the solar dynamo (Karak 2023). Lemerle et al. (2015) have first proposed that tilt quenching, which refers to the reduction of the tilt of Bipolar Magnetic Regions (BMRs) due to the presence of a strong magnetic field, can serve as the required nonlinearity in Babcock–Leighton dynamo models. Subsequently, Karak and Miesch (2017, 2018) incorporated tilt quenching in their dynamo models and achieved great success in reproducing the observed behavior of the solar cycle. More recently, Jha et al. (2020, 2023) utilized magnetogram data from the Michelson Doppler Imager (MDI) and the Helioseismic and Magnetic Imager (HMI) to provide observational evidence of tilt quenching. Additionally, Jha et al. (2020) demonstrated that the distribution of the maximum magnetic field in BMRs exhibits a double peak in their distribution.

One limitation of the work by Jha et al. (2020, 2023) is that they counted each BMR multiple times in their analysis, potentially impacting the inferences drawn from their results. To address this issue, Sreedevi et al. (2023); Sreedevi and Jha (2023) recently developed an algorithm based on feature association techniques to track BMRs in magnetograms more accurately. Here, we revisit the work done by Jha et al. (2020) and aim to determine whether the signature of tilt quenching reported by them can still be obtained from the tracked BMRs. Additionally, we investigate how the distribution of $B_{\rm max}$ changes with the tracked information of BMRs

2. Data and Method

We use the line of sight (LOS) magnetograms from the MDI (1996 – 2011) and HMI (2011 – 2022) to identify the BMRs and track them through during the period when they are in the near side of the Sun. The detection algorithm consist of identification of strong magnetic field regions followed by a moderate flux balance condition to make sure the detected regions are BMRs. This identification algorithm is similar to the one used in Stenflo and Kosovichev (2012) and Jha et al. (2020). Recently Sreedevi et al. (2023) has taken another step and developed an automatic tracking algorithm for BMRs (AutoTAB) to track the BMRs identified by Jha et al. (2020). The AutoTAB uses the features association technique, similar to one used by Jha et al. (2021) for sunspots tracking, to track the BMRs during its passage in the near side of the Sun. The AutoTAB provides a BMRs catalog with the properties of the BMRs such as total flux, location, maximum field ($B_{\rm max}$), average field. Therefore, we use these properties of the BMRs to re-analyse the results obtained in Jha et al. (2020).

3. Results

3.1. *Distribution of* $B_{\rm max}$

Jha et al. (2020) has reported that the $B_{\rm max}$ show a bimodal distribution with one peaks close to 600 G and another close to 2000 G. These peaks get well seprated when they classified the BMRs based on their signature in white-light continuum images. They reported that the peak corresponding to 600 G does not show any signature in white-light images i.e., they are not sunspots whereas other peak show a prominent signature for the same. This observed behaviour raised the question that, since in their work they have counted each BMRs multiple times it may be possible that they have picked the BMRs in their different phases and that gives rise to this observed double peak behavior. AutoTAB gives us an opportunity to track the BMRs and explore the distribution of $B_{\rm max}$ in them. In Figure 1, we show the distribution of $B_{\rm max}$, in which each BMRs are counted only once and the $B_{\rm max}$ of BMRs is determined at the point of time where $B_{\rm max}$ of BMRs peaks during their evolution. We noted that the distribution of $B_{\rm max}$ in BMRs are indeed bimodal with peaks at 600 G and 2 kG. At this point we do not have the answer why the $B_{\rm max}$ in BMRs show such distribution, it will be worth exploring in the future. In Figure 1 we also note that at many places the normalized fraction of BMRs exceed the fraction reported by Jha et al. (2020). This is because the AutoTAB uses the data with higher cadence and for longer period.

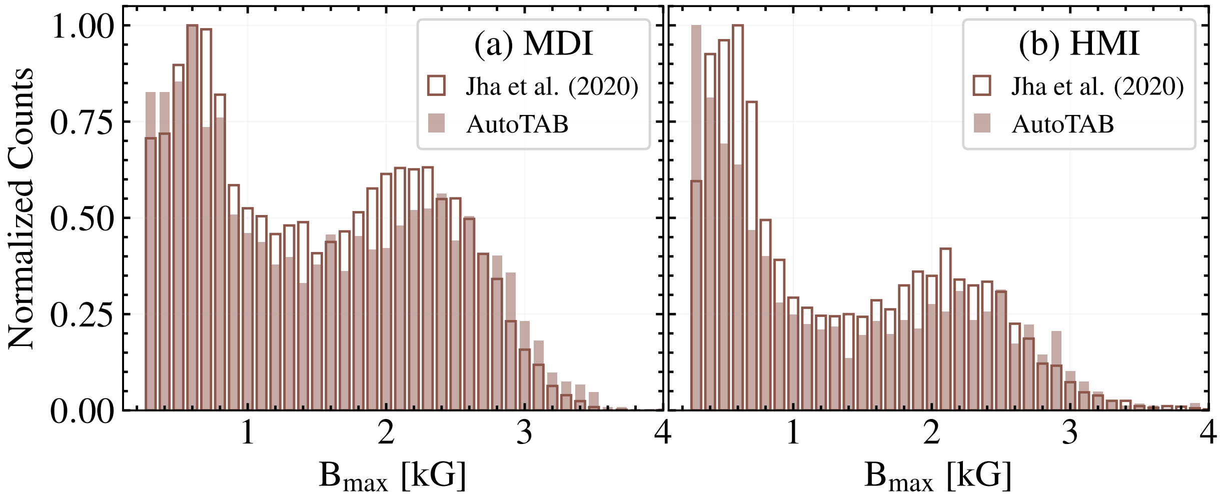

Figure 1. Normalized distribution of B_{max} for BMRs tracked using AutoTAB represented by filled bars and Jha et al. (2020), shown by unfilled bars.

3.2. *Tilt Quenching*

Tilt quenching is the phenomena of reduction in tilt on top of Joy's law because of the stronger magnetic field in it. The idea of tilt quenching was given by D'Silva and Choudhuri (1993), where they have explained the origin of tilt in the BMRs. Late, Lemerle et al. (2015) and Karak and Miesch (2017, 2018) has used tilt quenching in their solar cycle model. Jha et al. (2020) gave the first direct evidence of tilt quenching in observation (Figure 2(a)). In contrast with Jha et al. (2020), where they have counted each BMR many times, here we used the AutoTAB to track the BMRs and use its tilt when the flux in the BMRs is maximum during their evolution. Tracking of BMRs has significantly reduced the number of data point and hence we can not look at the B_{max} dependence of tilt in the way Jha et al. (2020) has looked at. Therefore we calculate the γ_0 of Joy's law which is $\gamma = \gamma_0 \sin\theta$ for each BMR in each B_{max} bin of size 500 G. Here, γ and θ is the tilt and latitude of BMRs, whereas γ_0 is called the amplitude of Joy's law. In Figure 2(b), we show the average of γ_0 calculate in each B_{max} bin along with the standard error as a function of B_{max}. In Figure 2(b) we note that the $\langle\gamma_0\rangle$ have quite different value compared to the Figure 2(a), but still we can the similar trend in $\langle\gamma_0\rangle$ which show the downward trend after 2.5 kG instead of 2.0 kG. We emphasize here that this is the very preliminary result and detailed discussion will be reported in future publication.

4. Conclusion

In this article, we extend the work of Jha et al. (2020) by utilizing the newly developed BMR tracking algorithm AutoTAB (Sreedevi et al. 2023). AutoTAB was implemented on the LOS magnetogram data from MDI and HMI to track the BMRs during their passage on the near side of the Sun. The distribution of B_{max} in BMRs shows a bimodal distribution similar to the one reported in Jha et al. (2020), where they counted BMRs multiple times, unlike in this work. We also examine the variation of $\langle\gamma_0\rangle$ as a function of B_{max}, showing a similar signature of tilt quenching as reported in Jha et al. (2020). Since we calculate the average of γ_0 for each BMR in a 500,G B_{max} bin, instead of fitting Joy's law, the values of $\langle\gamma_0\rangle$ differ from γ_0. These are preliminary results, and further details will be reported in an upcoming publication.

References

Babcock, H. D. 1959, The Sun's Polar Magnetic Field. *ApJ*, 130, 364.

Babcock, H. W. 1961, The Topology of the Sun's Magnetic Field and the 22-YEAR Cycle. *ApJ*, 133, 572.

Biswas, A., Karak, B. B., & Cameron, R. 2022, Toroidal Flux Loss due to Flux Emergence Explains why Solar Cycles Rise Differently but Decay in a Similar Way. *Phys. Rev. Lett.*, 129(24), 241102.

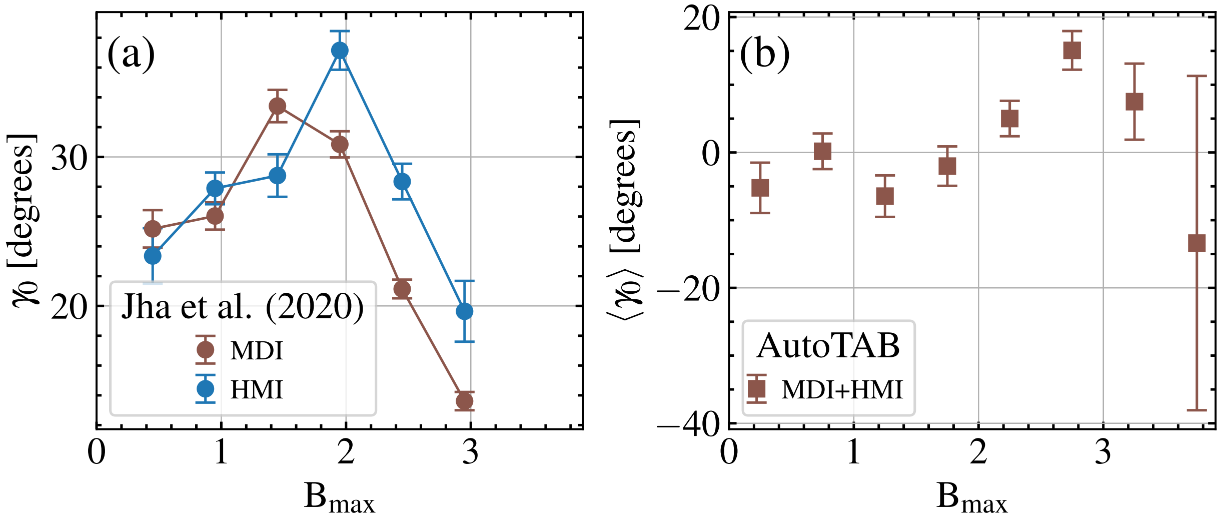

Figure 2. (a) The amplitude of Joy's law (γ_0) as a function of $B_{\rm max}$ for MDI and HMI, taken from Jha et al. (2020). (b) Average of amplitude of Joy's law ($\langle\gamma_0\rangle$) calculated over BMRs in 500 G $B_{\rm max}$ bin as a function of $B_{\rm max}$.

Charbonneau, P. 2014, Solar dynamo theory. *Ann. Rev. Astron. Astrophys.*, 52(1), 251–290.

D'Silva, S. & Choudhuri, A. R. 1993, A theoretical model for tilts of bipolar magnetic regions. *A&A*, 272, 621.

Jha, B. K. 2022,. *Long-term Study of the Sun and Its Implications to Solar Dynamo Models*. PhD thesis, Pondicherry University.

Jha, B. K., Karak, B. B., & Banerjee, D. 2023, Observational Signature of Tilt Quenching of Bipolar Magnetic Regions in the Sun. *IAU Symposium*, 372, 86–87.

Jha, B. K., Karak, B. B., Mandal, S., & Banerjee, D. 2020, Magnetic Field Dependence of Bipolar Magnetic Region Tilts on the Sun: Indication of Tilt Quenching. *ApJ Letters*, 889(1), L19.

Jha, B. K., Priyadarshi, A., Mandal, S., Chatterjee, S., & Banerjee, D. 2021, Measurements of Solar Differential Rotation Using the Century Long Kodaikanal Sunspot Data. *Solar Phys.*, 296(1), 25.

Karak, B. B., Jiang, J., Miesch, M. S., Charbonneau, P., & Choudhuri, A. R. 2014,a Flux Transport Dynamos: From Kinematics to Dynamics. *Space Sci. Rev.*, 186a, 561–602.

Karak, B. B. 2020, Dynamo Saturation through the Latitudinal Variation of Bipolar Magnetic Regions in the Sun. *ApJ Letters*, 901(2), L35.

Karak, B. B. 2023, Models for the long-term variations of solar activity. *Living Reviews in Solar Physics*, 20(1), 3.

Karak, B. B. & Miesch, M. 2017, Solar Cycle Variability Induced by Tilt Angle Scatter in a Babcock-Leighton Solar Dynamo Model. *ApJ*, 847, 69.

Karak, B. B. & Miesch, M. 2018, Recovery from Maunder-like Grand Minima in a Babcock – Leighton Solar Dynamo Model. *ApJ Letters*, 860, L26.

Lemerle, A., Charbonneau, P., & Carignan-Dugas, A. 2015, A Coupled 2 × 2D Babcock-Leighton Solar Dynamo Model. I. Surface Magnetic Flux Evolution. *ApJ*, 810, 78.

Sreedevi, A., Jha, B. K., Karak, B. B., & Banerjee, D. 2023, AutoTAB: Automatic Tracking Algorithm for Bipolar Magnetic Regions. *ApJ Supplement*, 268(2), 58.

Sreedevi, A. B. & Jha, B. K. 2023, Automatic Algorithm for Tracking Bipolar Magnetic Regions. *IAU Symposium*, 372, 97–99.

Stenflo, J. O. & Kosovichev, A. G. 2012, Bipolar Magnetic Regions on the Sun: Global Analysis of the SOHO/MDI Data Set. *ApJ*, 745, 129.