Observational study of bipolar magnetic regions: Support of thin-flux tube rise?

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Abstract

The Bipolar Magnetic Regions (BMRs) are the strong magnetic feature, consisting of two magnetic polarities, separated by a neutral line, observed on the surface of the Sun. They are found to be tilted with the equator, which statistically increases with their latitudes. This is popularly known as Joy's Law. The thin flux tube model suggests that the magnetic field concentrated in flux tubes rises from the base of the convection zone to emerge as BMRs on the surface. As flux tubes rise, torque induced by the Coriolis force acting on diverging flows developed at the apex of tubes produces the tilt in the BMRs. Despite the popularity of the rising flux tube model as an explanation for the formation of BMRs, observational supports are limited. In this work, we study the evolving properties of BMR throughout their lifetimes by analyzing line-of-sight magnetograms from Michelson Doppler Imager (MDI) and Helioseismic and Magnetic Imager (HMI) for the past two solar cycles. Our analysis employs an automatic detection algorithm and an in-house developed automatic algorithm for tracking the BMRs to study their evolution. The evolutions of BMR tilt, foot separation, and magnetic properties hint at the theory of rising thin flux tubes behind the formation of BMRs and tilt quenching as a possible mechanism for quenching in Babcock-Leighton dynamo model.

Introduction

- The **B**ipolar **M**agnetic **R**egions (**BMR**s) are intense magnetic field regions on the surface of the Sun and act as a proxy for global solar magnetism and its variability.
- They are tilted with respect to the East-West line –**Tilt Angle**. The tilt angle is found to increase statistically with respect to latitudes, commonly known as Joy's Law. Tilt is crucial for the generation and reversal of polar magnetic field in solar dynamo.
- Thin flux-tube rising model is one of the theories which explains the formation of BMRs. It suggests that magnetic flux tubes rise from the convection zone due to magnetic buoyancy. Rising flux tube experiences coriolis force at its apex to produce the tilt in BMRs.

Objective

The aim of this study is to investigate the BMRs throughout their lifespan and examine the potential role of the thin flux tube model in the generation of the BMRs.

Data and Methodology

- We use line-of-sight magnetograms from space-borne instruments (Michelson Doppler Imager (MDI) and Helioseismic and Magnetic Imager (HMI)) for the period of 1996-2020 with a 96 minute cadence to detect and track the BMRs.
- For the automatic detection of BMRs from LOS magnetograms, we use the same recipe as prescribed by Stenflo and Kosovichev, 2012, by isolating flux-concentrated regions and applying flux balance conditions on them. The identified BMRs are stored in the form of binary maps.
- Our tracking algorithm, AutoTAB (Automatic Tracking Algorithm for Bipolar Magnetic Regions), can automatically track BMRs by utilizing binary maps generated by our detection algorithm. This is achieved by differentially rotating the binary maps of the identified regions and examining their degree of overlap.
- We find that AutoTAB excels in tracking, even for the small features, and it successfully tracks 9152 BMRs over the last two solar cycles (1996–2020), providing a comprehensive dataset that depicts the evolution of various positional, magnetic, and morphological properties for each tracked region.

A case study

To show a representative result of our tracking algorithm, we show the evolution of NOAA AR8048 in Figure 1. AR08048 was tracked by AutoTAB from 1997-05-31T22:25 for the next 7 days with 65 observations in between. In Figure 1(a-g) we show only stages of its evolution with a cadence of one day. AR08048 was first identified near the East limb (29.6 S, -45.7 E) until it decays near West limb (29.6 S, 35.2 E). Further, in Figure 1(h) shows the evolution of absolute total flux and $B_{\max}$ over the tracked duration, where we see that both the quantities increase over the initial phase of BMR's lifetime and saturates towards its end phase. Hence, AutoTAB tracks the BMR from its birth to the time it starts decaying and stops holding a decent flux balance condition, which can also be inferred from the snapshots.

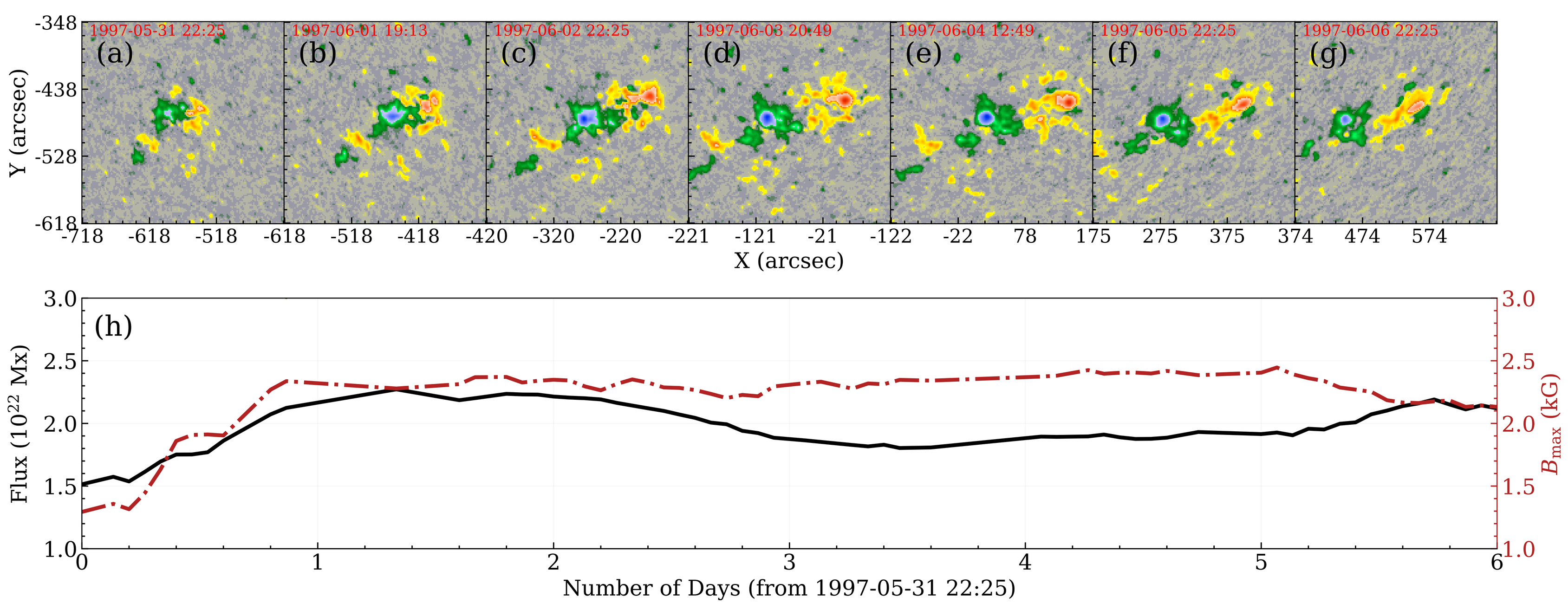

Figure 1. Panels (a)-(g) show the snapshots of the tracked BMR NOAA AR8048 corresponding to each day during the tracking. Panels (h) show the evolution of absolute total flux and Bmax for the BMR.

Classification of the tracked BMRs

It has been observed that BMRs display a wide spectrum of lifetimes, ranging from a few hours to more than a week. In certain instances, AutoTAB only monitors the BMRs while they are visible on the solar disk. Additionally, tracking of certain BMRs may be incomplete or irregular due to missing or corrupted data. Consequently, the tracked BMRs are classified into three distinct categories.

- **Short lived (SL):** BMRs that live for less than 8 hours from their first detection.
- **Lifetime (LT):** BMRs that have a lifetime of more than 8 hours, and they emerge and decay in the near side of the sun.
- **Diskpassage (DP):** BMRs that have not been tracked through their lifetime, we only track them in a part of their evolutionary phase. Such BMRs continue to live on the far side of the Sun.

Classification	Number of BMRs	Area $\pm\Delta$Area (μHem)	Flux $\pm\Delta$Flux (10^{22}Mx)	$B_{\max}\pm\Delta B_{\max}$ (G)	$B_{\mathrm{mean}}\pm\Delta B_{\mathrm{mean}}$ (G)
Short Lived (SL)	1251	20.17 ± 0.71	0.26 ± 0.01	541.32 ± 5.38	197.46 ± 0.66
Lifetime (LT)	3191	88.65 ± 1.05	1.50 ± 0.02	949.20 ± 6.35	224.46 ± 0.81
Disk Passage (DP)	4710	116.87 ± 0.17	2.05 ± 0.01	1436.83 ± 7.02	281.07 ± 0.71

Figure 2. Some key parameters of different classes of tracked BMRs

Results and Discussion

One of the important properties observed in sunspots is their latitudinal distribution with time, known as the butterfly diagram. Figure 3 represents the latitudinal distribution of the BMRs from three different classes, represented by three different colors. Here, each point represents a unique BMR. The latitude and time of all the BMRs are chosen at a time when they attain their maximum total flux. Here we note that BMRs of classes Diskpassage and Lifetime follow the familiar butterfly diagram, but BMRs in Short lived class do not show such a behavior.

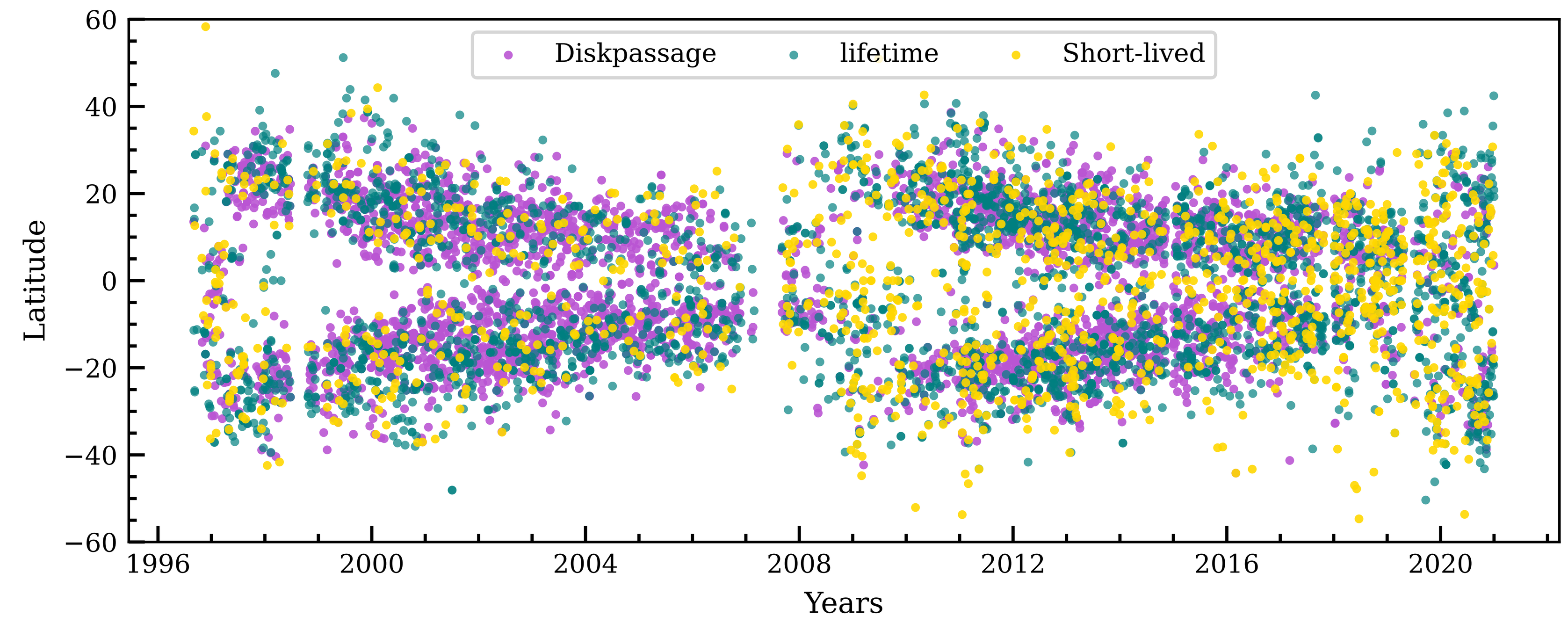

Figure 3. Butterfly diagram of the tracked BMRs. Different colors represent the BMRs of different categories.

After analyzing the evolution of various properties of LT BMRs throughout their normalized lifetime, we observed a systematic increase in footpoint separation until halfway through their lifespan, followed by saturation in the final phase as represented in Figure 4. A similar kind of trend is also observed in the case of the behavior of tilt as shown in Figure 5.

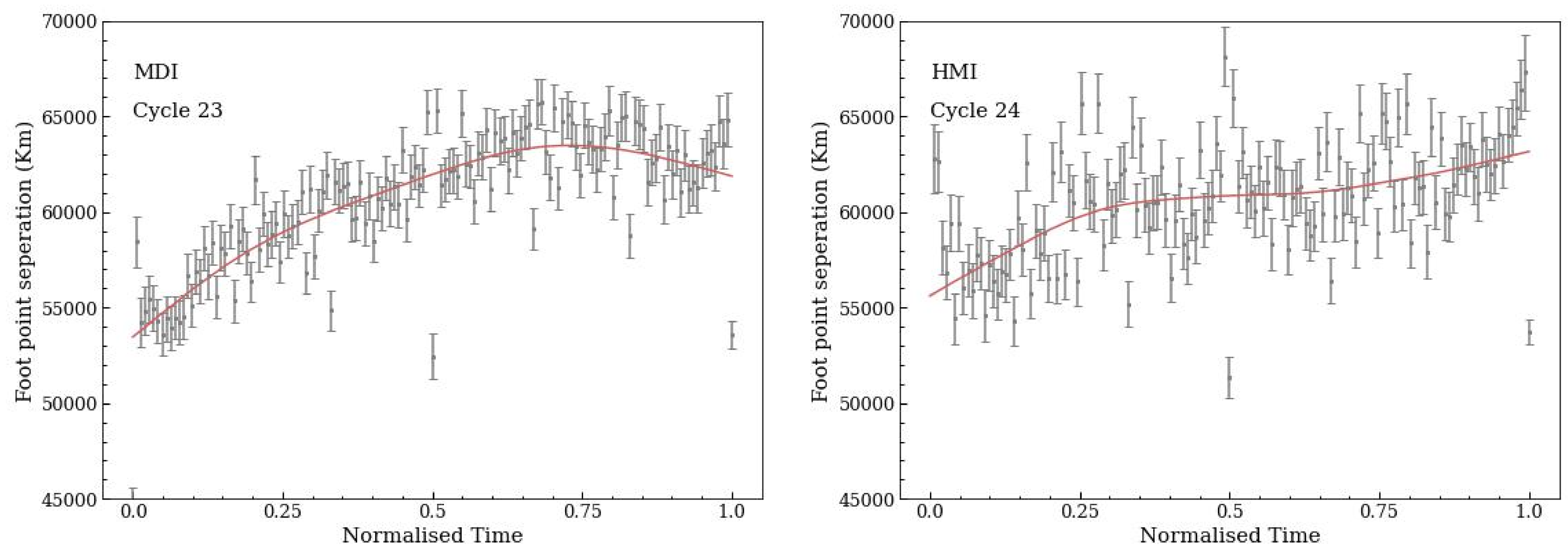

Figure 4. Evolution of footpoint separation of BMRs over their normalized lifetime.

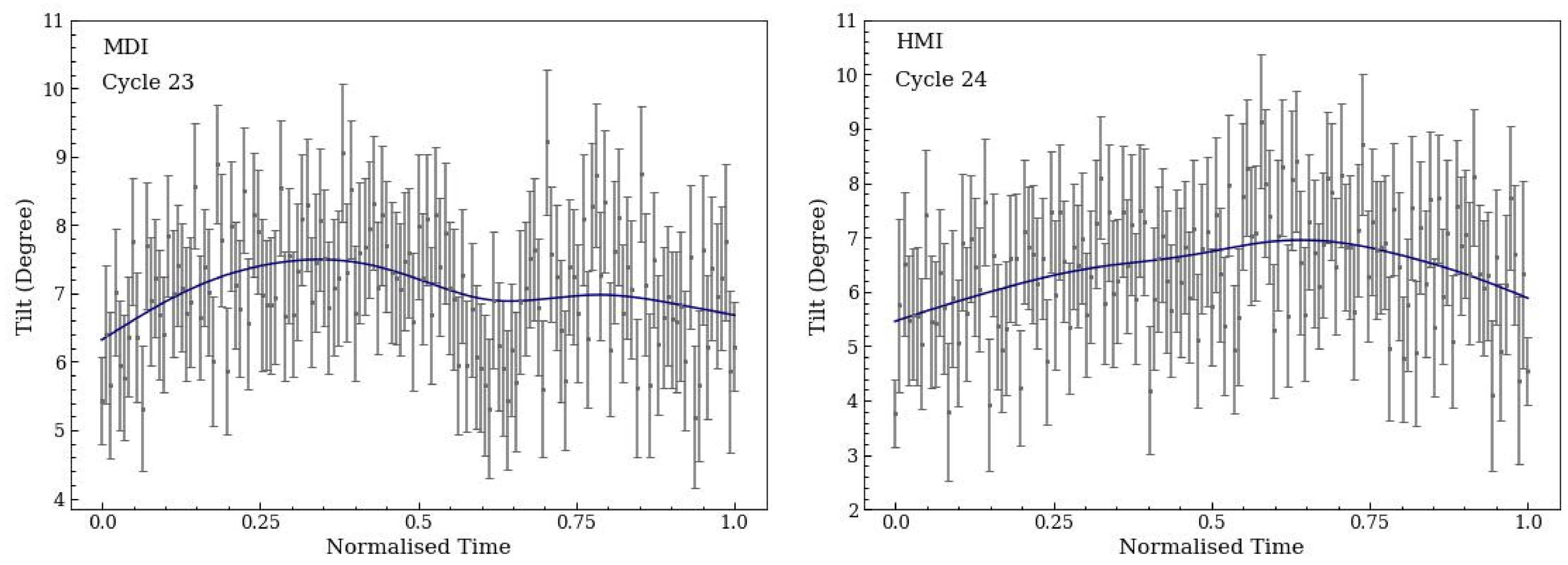

Figure 5. Evolution of tilt of BMRs over their normalized lifetime.

Similarly, for magnetic properties, Figure 6 illustrates the variation of absolute total flux and $B_{\max}$ over the normalized lifetime. Our findings indicate that both flux and $B_{\max}$ decline during the first half of the lifespan and then increase in the latter half.

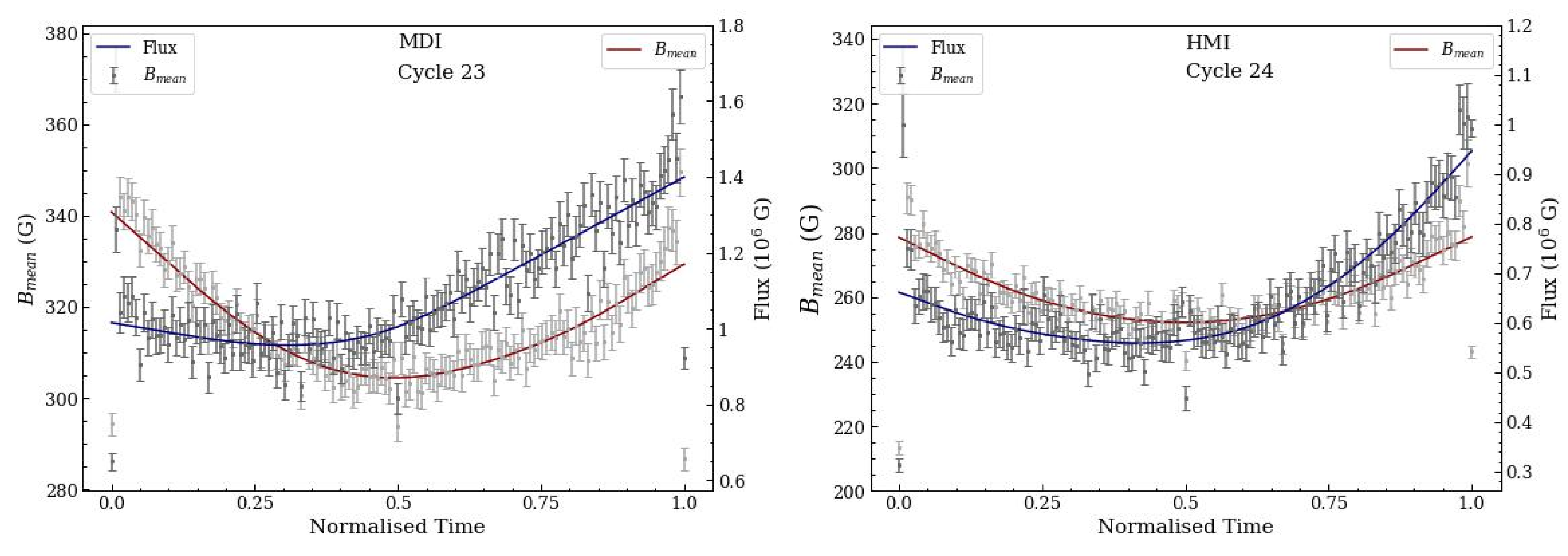

Figure 6. Evolution of absolute total flux and $B_{\max}$ of BMRs over their normalized lifetime.

Conclusion

- Using our newly developed, fully automated algorithm, we have detected and tracked the BMRs from the line-of-sight magnetograms of the last two solar cycles.
- We find that both footpoint separation and tilt increase in the initial phase of BMRs lifetime and saturate in the later phase.
- We see an anti-correlation between the evolution of the magnetic field and tilt.
- The increasing footprint separation throughout the lifespan of BMRs lends support to the hypothesis of flux tubes rising from the convection zone. Moreover, the observed anti-correlation between the magnetic field and tilt provides compelling evidence in favor of the thin flux tube rising model.

Reference

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