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Magnetic Flux Density as a Driver of Chromospheric and Coronal Emissions During the Rise of Solar Cycle 25

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Abstract

This study investigates the relationship between magnetic flux density (MFD) and key solar proxies (f10.7 cm radio flux, Mg II index, and Ca II K-line) during the ascending phase of Solar Cycle 25. Strong linear ($r = \mathbf{0.94-0.96}$) and monotonic ($\rho = \mathbf{0.85}$) correlations indicate that solar magnetic fields are the primary drivers of chromospheric and coronal emissions. The temporal hierarchy revealed by correlogram analysis shows that MFD leads the chromospheric indices by 33 days, while it has no lag with f10.7 cm, which is significant for space weather prediction. Wavelet analysis further identifies synchronized variability on 16–32 day timescales associated with solar rotation, reflecting coherent periodic behavior across different layers of the solar atmosphere.

Keywords: Solar cycle, solar Activity, solar activity Proxies, Ascending Phase, Magnetic flux density

1 Introduction

Understanding the role magnetic fields plays in space weather is essential for predicting and characterizing solar terrestrial interactions ([Hathaway et al. 1999](#); [Gopalswamy](#)

et al. 2022). The Sun’s magnetic field can directly be observed and measured through active phenomena such as sunspots, solar flares, coronal heating, prominences, filaments, and coronal mass ejections (CMEs) (Filippov 2024). The origin and evolution of the Sun’s magnetic field are governed by the solar dynamo, a process that also drives the regular variations in solar activity observed as the solar cycle (SC) (Ruzmaikin 1985; Balogh et al. 2014; Hathaway 2015; Charbonneau 2020).

The solar cycle, which sometimes is referred to as the Schwabe cycle, can be characterized by periodic variations in the magnetic activity with an average duration of approximately 11 years (Russell et al. 2010). It typically progresses through four distinct phases: solar minimum, ascending, maximum, and descending phases (Sawadogo et al. 2024).

Variations in solar activity can be estimated using various proxies such as Mg II, Lyman α irradiance, Ca II H & K emission, sunspot number, and the 10.7 cm radio flux (f10.7cm) (Duran et al. 2024). These Solar activity proxies trace magnetic field driven process in the solar atmosphere and they are used when long-term, consistent measurements of solar ionizing radiation are not available (Trujillo Bueno and del Pino Alemán 2022; Usoskin 2023).

An important factor influencing these proxies is the Sun’s rotation. The Sun rotates on its axis approximately once every 27 days but not all parts rotate at the same speed for instance the sun spins faster at the equator (25 days) and substantially slower near the poles (31 days) (Howe 2009). As a result, solar activity proxies exhibit quasi-periodic variations on timescales of the solar rotation (Fioletov 2009).

Despite the widespread application of solar activity proxies, they do not directly measure the magnetic fields. instead they respond to atmospheric heating and emission processes that are ultimately driven by magnetic activity.

A study by Benevolenskaya and Kostuchenko (2013) reveals how models and datasets often lack the spatial and temporal resolution needed to capture rapid, short-term magnetic dynamics. These limitations highlight the need for magnetic-field-based indices that more directly quantify solar magnetic variability, providing an opportunity to utilize high-resolution SDO data. In this regard, Shukure et al. (2021) determined the magnetic flux density (MFD) and examined its relationship with sunspot area. However, their analysis was limited to the solar minimum and maximum phases of Solar Cycle 24. Moreover, the MFD time series was constructed using only strong magnetic flux densities ($B \geq 800$ G). Therefore, further investigation of weak MFD across other phases of solar activity is required.

In this study, we aim to validate the newly determined weak MFD index by examining its consistency with established solar activity proxies (Mg II , Ca II K, and the f10.7 cm) during the ascending phase of SC 25. We apply time-series analysis techniques (Continuous Wavelet Transform (CWT) and Cross Wavelet Transform (XWT)), cross correlation, corelogram analysis and statistical methods to study temporal variations and phase relationships.

We utilized high-resolution solar magnetic flux density data from Solar Dynamic Observatory (SDO)/Helioseismic Magnetic Imager (HMI) which was extracted from the magnetogram. The HMI computes a 720-second average using a temporal filter applied to 1215 seconds of data Liu et al. (2012). Section 2 presents the data sets

used in this study and Section 3 describes the methodology. The corresponding results and discussion detailed in section 4. Section 5 summarizes the study and provides the overall conclusions.

2 Datasets

2.1 Magnetic Flux Density (MFD)

The magnetic field is most frequently measured in the photosphere, where observations are most consistent and detailed by [Parker \(1970\)](#); [Wiegmann et al. \(2014\)](#). While direct measurements in the chromosphere and corona are less common and more challenging they still rely on the same fundamental principle, the Zeeman effect, which detects magnetic fields through the splitting of spectral lines ([Trujillo Bueno and del Pino Alemán 2022](#)).

In this study, we used data obtained from the HMI on board of the SDO. The HMI instrument delivers continuous measurements of the line-of-sight magnetic field, which makes it particularly suitable for tracking how solar magnetic activity changes over time. HMI operates with two charge-coupled device (CCD) cameras, using exposure times of 45 s and 720 s [Scherrer et al. \(2012\)](#). Each camera has a 4096×4096 pixel detector, producing full-disk magnetograms with a spatial resolution of about one arc-second with a 0.5 pixel size [Liu et al. \(2012\)](#).

The data consisted of a maximum of 15 magnetograms per day in raw FITS file format. We analyzed the total of 96 minute aggregated magnetogram data from 2020 to 2024, in alignment with the solar ascending phase of SC 25. Following the procedures outlined by [Howard et al. \(1983, 1980\)](#); [Ulrich et al. \(1991\)](#); [Li et al. \(2014\)](#); [Xiang et al. \(2014\)](#); [Xiang and Kong \(2015\)](#) and the method presented by [Shukure et al. \(2021\)](#), we calculate the weak MFD in the following manner: initially, we identified pixels with magnetic flux magnitude ranging from 100 G to 800 G. Subsequently, we summed these selected pixel values and divided them by the total disc's area. This process was iterated across all datasets from the specified years. Finally, we derived the daily average of the MFD.

Mathematically, the MFD at time t is defined as

$$\text{MFD}(t) = \frac{1}{A_{\odot}} \sum_{i=1}^{N(t)} |B_i|, \quad 100 \text{ G} \leq |B_i| \leq 800 \text{ G}, \quad (1)$$

where B_i represents the magnetic flux density of the i -th pixel, $N(t)$ denotes the number of pixels that satisfy the selected magnetic flux range at time t , and $A_{\odot}$ is the total projected area of the solar disk. We carried out this process using the Python script to generate daily average magnetic flux density signal.

2.2 The 10.7 cm Solar Radio Flux (f10.7cm)

The f10.7 cm is a widely used global indicator of solar magnetic activity. As a solar proxy, it is routinely employed as an input parameter in models that calculate atmospheric density for satellite orbit determination and in predicting ionospheric

effects on radio wave propagation and communication systems (Huang et al. 2009). The f10.7cm data used in this study was sourced from NOAA’s Space Weather Prediction Center (SWPC) and LASP’s LISIRD <https://lasp.colorado.edu/lisird/>.

2.3 Chromospheric Activity Proxies

The Calcium II K index (Ca II K) and the Magnesium II index (Mg II) are both important indicators of solar chromospheric activity (Dudok de Wit et al. 2009; DeLand and Marchenko 2013; Ermolli et al. 2018). They are closely linked to solar magnetic fields and are widely used to study the Sun’s magnetic behavior and to model solar UV radiation (Chatzistergos et al. 2021). Both of the indices were obtained from NASA’s Solar Backscatter Ultraviolet (SBUV) archive <https://sbuv.gsfc.nasa.gov/solar/omi/>.

3 Method

3.1 Correlation Analysis

In this study, we employed both the Pearson and Spearman correlation analyses to provide a comprehensive assessment of the relationships between the variables. The Pearson correlation coefficient (r) is a statistical approach that quantifies the strength and direction of the linear relationship between two variables, under the assumption that each variable is normally distributed (Steuer et al. 2002; Omar et al. 2022). The formula for the Pearson correlation coefficient (r) is given by de Siqueira Santos et al. (2014):

$$r = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2} \sqrt{\sum_{i=1}^n (y_i - \bar{y})^2}}. \quad (2)$$

x_i and y_i represent the individual data points of the two variables, $\bar{x}$ and $\bar{y}$ denote their respective means, and n is the total number of observations.

The Spearman’s correlation measures the monotonic relationship between the two variables (de Siqueira Santos et al. 2014)

$$\rho = 1 - \frac{6 \sum d_i^2}{n(n^2 - 1)}. \quad (3)$$

In the formula, ρ is the Spearman rank correlation coefficient, d_i is the rank difference for each pair, and n is the number of observations. The constant 6 comes from simplifying the formula using the least squares method.

The correlation coefficients r and ρ , range from -1 to 1 , where 1 indicates a positive relationship, -1 represents a perfect negative relationship, and 0 denotes no correlation between the variables.

3.2 Correlogram Analysis

The correlogram is a technique used for quantifying the relationship between two signals or time series as a function of time lag (Bourke 1996). We used the correlogram

to identify the time lag between (a) MFD and f10.7 cm (b) MFD and Mg II index, and (c) MFD and Ca II K-line.

3.3 Continuous Wavelet Transform (CWT)

CWT is a method for analyzing signals $f(t)$ that vary in both time and frequency. This approach reveals periodic patterns in $f(t)$ at specific scales, making it easier to detect temporal features. Unlike Fourier analysis, which loses time information, the CWT preserves temporal locality, making it especially useful for non-stationary or irregularly sampled data, where distortions from uneven sampling are minimized (Kelly et al. 2003). For a discrete signal $x_{n'}$, the CWT is defined as the convolution of $x_{n'}$ with a wavelet that has been both scaled and normalized (Grinsted et al. 2004; Benevolenskaya and Kostuchenko 2013):

$$W_n(s) = \sum_{n'=0}^{N-1} x_{n'} \psi^* \left(\frac{(n' - n)\delta t}{s} \right), \quad (4)$$

where $W_n^X(s)$ represents the wavelet coefficient at scale s and time index n . The term $x_{n'}$ denotes the discrete signal values, and ψ^* is the complex conjugate of the mother wavelet. The argument $\frac{(n' - n)\delta t}{s}$ adjusts the wavelet in both time and scale.

One of the most widely used mother wavelets in the Continuous Wavelet Transform (CWT) is the Morlet wavelet, defined by Grinsted et al. (2004); Benevolenskaya and Kostuchenko (2013):

$$\psi_0(\eta) = \pi^{-1/4} e^{i\omega_0\eta} e^{-\eta^2/2}, \quad (5)$$

where ω_0 is the dimensionless frequency, typically set to 6. This choice satisfies the admissibility condition, which ensures that the wavelet has zero mean and is suitable for inverse transforms. The scale parameter is denoted by s , and $\eta = \frac{t}{s}$ represents the non-dimensional time variable used in the wavelet function.

3.4 Cross-wavelet Transform (XWT)

The XWT is a powerful technique used to identify common periods between two time series and analyze the temporal variability as defined in Grinsted et al. (2004); Benevolenskaya and Kostuchenko (2013) is given as:

$$W_{XY}(a, b) = W_Y(a, b)W_X(a, b)^*, \quad (6)$$

where $W_X(a, b)$ and $W_Y(a, b)$ denote the wavelet transforms of the time series $y(t)$ and $x(t)$, with “*” representing the complex conjugate of the transform. The cross-wavelet spectrum is complex, and the cross-wavelet power is defined as its magnitude $|W_{XY}(s)|$ (Grinsted et al. 2004; Shukure et al. 2021).

4 Results And Discussion

Figure 1 presents the daily data of MFD, Mg II, f10.7 cm, and Ca II K, plotted as a function of time. The horizontal axis represents day number of years from 2020 to 2024, while the vertical axis shows the corresponding normalized values of each parameter, illustrating their overall trends.

Between days 1 and 325 (marked by the purple vertical lines), we observed a slow but steady increase in the slope, representing the transition from the solar minimum to the ascending phase of the cycle, often referred to as the quiet phase, where solar activity is still low and magnetic flux emergence is limited (Usoskin 2023). Around day 495, a brief decline in f10.7 cm was noticed which is indicated by the yellow vertical line, this suggest a short-term fluctuations. Around day 730, a noticeable increase is observed across all parameters most especially in the MFD and f10.7 cm radio flux, as indicated by the green line, marking a clear transition toward heightened solar activity. Beyond this period, the curves continued to rise steadily and reach peak activity around day 1630 (red broken vertical line), which mark as a transition into Solar maximum.

Figure 2 displays Pearson and Spearman scatter plots comparing the MFD with (a) the f10.7 cm, (b) the Mg II index, and (c) the Ca II K-line index. The f10.7 cm shows a strong linear and monotonic correlation with MFD, with a coefficient of r and ρ , respectively, to be 0.96. This means that changes in f10.7cm correspond almost perfectly to changes in MFD. The chromospheric Mg II and Ca II K indices displays a similarly strong correlations with MFD. For both indices, the Pearson correlation coefficient reaches $r = 0.95$, while the Spearman coefficient is $\rho = 0.94$, indicating a consistently tight association across different correlation measures. These results confirm the Li et al. (2025) finding that the f10.7 cm radio flux and chromospheric indices serve as reliable proxies for photospheric magnetic flux, demonstrating that the solar magnetic field is the primary driver of atmospheric emission. The Henze–Zirkler (HZ) test statistics values are extremely small ranging in 10^{-6} to 10^{-5} , indicating only negligible departures from multivariate normality.

The wavelet power spectrum shown in Figure 3 presents the MFD, Mg II index, Ca II K-line, and f10.7 cm, was computed using the Morlet wavelet as defined in Eq. 4. The vertical axis represents the period (in days), while the horizontal axis shows time also in days, ranging from 2020 to 2024. The plot shows dominant areas of high power surrounded by thick black contours that represent significant areas at the 95% confidence level (CI), calculated using Monte Carlo simulations (Torrence and Compo 1998). A thin black curved line represents the cone of influence, marking the region where wavelet coefficient estimates become unreliable due to edge effects. Outside this boundary, results are considered statistically insignificant 5% significance level (Kolev and Chapanov 2023).

As the ascending phase progressed, a pronounced concentration of wavelet power was observed between days 680–1050 (marked by white lines), 1060–1280 (marked by purple lines), and 1360–1740 (marked by red lines). This power predominantly within the 16–32 day scale range, which encompasses the characteristic solar rotational period (~ 27 days). As detailed in Pap et al. (1990); Ma et al. (2012), this indicates modulation by solar rotation, which caused by low solar activity at the being of the ascending

phase. The Chromospheric indices and MFD displayed a broader regions of enhanced power this indicates that the photospheric and Chromospheric layers experience more persistent and widespread variability, likely due to the buildup of magnetic structures and plages [de Grijs and Kamath \(2021\)](#).

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Table 1 Correlation Coefficients and HZ Values Between MFD and Solar Proxies.

Correlation	f10.7 vs MFD	Mg II vs MFD	Ca II K vs MFD
Pearson	$r = 0.96$, HZ = 8.8×10^{-6}	$r = 0.95$, HZ = 9.1×10^{-6}	$r = 0.95$, HZ = 1.1×10^{-5}
Spearman	$\rho = 0.96$, HZ = 2.6×10^{-5}	$\rho = 0.94$, HZ = 1.2×10^{-5}	$\rho = 0.94$, HZ = 6.5×10^{-6}

power. This indicates that the photospheric and Chromospheric layers experience more persistent and widespread variability, likely due to the buildup of magnetic structures and plages [de Grijs and Kamath \(2021\)](#).

Contrary to that the f10.7 cm radio flux displayed more localized, narrow bursts of power. This is because, the temporal evolution of the f10.7 cm solar radio flux is primarily governed by emission from magnetically concentrated active regions, where thermal bremsstrahlung and gyroresonance processes dominate ([To et al. 2023](#)). Since these strong magnetic flux concentrations (e.g., sunspots and associated coronal structures) occupy only a small fraction of the solar disk, the f10.7 index preferentially reflects localized, high-field environments. In contrast, chromospheric proxies such as the Ca II K line and the Mg II index sample more spatially extended atmospheric layers, including both active regions and the pervasive magnetic network. Consequently, while f10.7 cm is a reliable proxy for solar activity, its variability is more strongly weighted toward compact magnetic structures than full-disk chromospheric emission ([Tapping 2013](#)).

The Correlogram in Figure 4 displays the time-lag relationships between proxies (Mg II, f10.cm and Ca II K) and the MFD. The chromospheric indices, Mg II and Ca II K against the MFD reveals a time lag of 33 days and correlation of $r = 0.889$ and $r = 0.892$, implies that changes in the photospheric MFD occur 33 days before corresponding changes in chromospheric activity. This highlights MFD as a leading indicator of chromospheric heating processes, agreeing with the studies by [Leenaarts et al. \(2018\)](#). While Mg II and Ca II K are less suitable for prediction, their delayed response provides an insight in the later stages of energy propagation ([Jess et al. 2015](#)), serving as useful diagnostics for tracking the vertical coupling of solar atmospheric layers following magnetic activity.

Meanwhile, the maximum correlation between f10.7cm and MFD occurs at a time lag of 0 days with a strong correlation of 0.962, which means that the solar activity indicators vary simultaneously without significant delay. Their early response enables forecasters to anticipate incoming solar energy deposition into the Earth’s upper atmosphere, which is critical for predicting effects such as increased satellite drag, ionospheric disturbances, and disruptions to radio communication.

Figure 5 presents the XWT analysis between magnetic flux density and solar activity proxies. In each panels (a), (b), and (c) regions of enhanced cross-power are prominently observed, particularly around the day 16–32 timescale. This range notably includes the Sun’s typical 27-day rotation period, which exhibits strong synchronized variability across solar parameters. The XWT spectrum displays a distribution of phase (arrows) is almost random, which indicate that it does not maintain a consistent phase relationship. Within the CI, we observed that the phase relationship between

the chromospheric indices (Mg II and Ca II K) and the MFD remains predominantly in phase during days 790–1010. The behavior shifts during days 1400–1690, where the paired indices exhibit a 45° in-phase, alternating between up-right and down-right orientations, indicating a more complex and intermittent phase relationship.

In the case of the f10.7 cm radio flux versus MFD, all the phase arrows within the CI points horizontally to the right. This signifies a consistent in-phase relationship ($\phi \approx 0^\circ$), indicating that the two time series vary synchronously with no measurable phase lag and strong evidence that increases in photospheric MFD are directly and immediately followed by increases in coronal radio flux (Benevolenskaya and Kostuchenko 2013; Xu et al. 2017). This finding validates the widespread use of f10.7 as a reliable real-time indicator of underlying solar magnetic activity for space weather and atmospheric studies (Huang et al. 2009; Henney et al. 2012).

Meanwhile, the coherence patterns between the Mg II and Ca II K indices and MFD are nearly identical, likely due to their shared chromospheric origin, which results in a similar response to MFD variations (de Wit et al. 2008; Dudok de Wit et al. 2009). In contrast, the f10.7 cm emission, compared with MFD, shows the smallest coherence interval. This is because it originates from the upper chromosphere and lower corona, making it less directly sensitive to small-scale variations in the photospheric magnetic flux (Henney et al. 2012; Bruevich and Yakunina 2013). These results have important implications on solar irradiance modeling and understanding magnetic energy transport through the solar atmosphere.

5 Conclusion

Our analysis shows that variations in photospheric magnetic flux, as captured by the weak MFD index, are closely linked to solar activity across multiple atmospheric layers. By applying complementary statistical and time-frequency approaches, we find consistently strong relationships between the MFD index and the established proxies Mg II, Ca II K, and f10.7 cm during the ascending phase of SC 25. The correlation analysis revealed a strong linear ($r = 0.95\text{--}0.96$) and monotonic ($\rho = 0.94\text{--}0.96$) relationship, indicating that variations in magnetic flux are the dominant drivers of chromospheric and coronal emissions (Li et al. 2025). At the being of the rising phase we noticed less or low solar activity in all methods applied this as well causes weak rotational modulation in solar indices (Pap et al. 1990). The correlogram shows that changes in MFD occur about 33 days before changes in the chromospheric indices, while the f10.7 cm flux changes almost simultaneously with MFD. This indicates that f10.7 cm is nearly synchronous with magnetic activity and can be useful for predicting space weather (Huang et al. 2009).

The wavelet transform reveals a synchronized 16–32 day variability tied to solar rotation, highlighting strong periodic and synchronized variability across different solar atmospheric layers. The CWT analysis shows that while chromospheric indices (Mg II, Ca II K) and MFD exhibit broad, sustained periods of enhanced power, the f10.7 cm flux displays sharper, more localized bursts, reflecting its acute sensitivity to transient events in the upper chromosphere and lower corona. The XWT demonstrates that MFD and chromospheric indices are largely in phase during certain intervals, with

intermittent deviations suggesting more complex interactions. In contrast, the f10.7 cm flux remains consistently in phase with MFD, confirming its role as a reliable real-time indicator of photospheric magnetic activity (Henney et al. 2012). Overall, our results improve the understanding of how photospheric magnetic flux relates to solar activity proxies. Changes in magnetic flux clearly drive most of the activity in the chromosphere and corona during the rising phase of SC 25. These solar activity proxies all react in different ways: the chromospheric indices shows slower, broader changes, while the f10.7 cm flux responds almost immediately and sharply, making it a good real time indicator of magnetic activity. These findings are important for improving models of solar irradiance, predicting space weather, and understanding how the Sun's different layers interact over time.

In the next study, we examine the relationship between the MFD index and UV irradiance during the ascending phase of SC 25.

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6 Declaration of generative AI and AI-assisted technologies in the manuscript preparation process

During the preparation of this work the author(s) used GPT-3.5 turbo for language correction. After using this tool/service, the author(s) reviewed and edited the content as needed and take(s) full responsibility for the content of the published article.

7 A conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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MFD index and Solar Proxies (2020-2024)

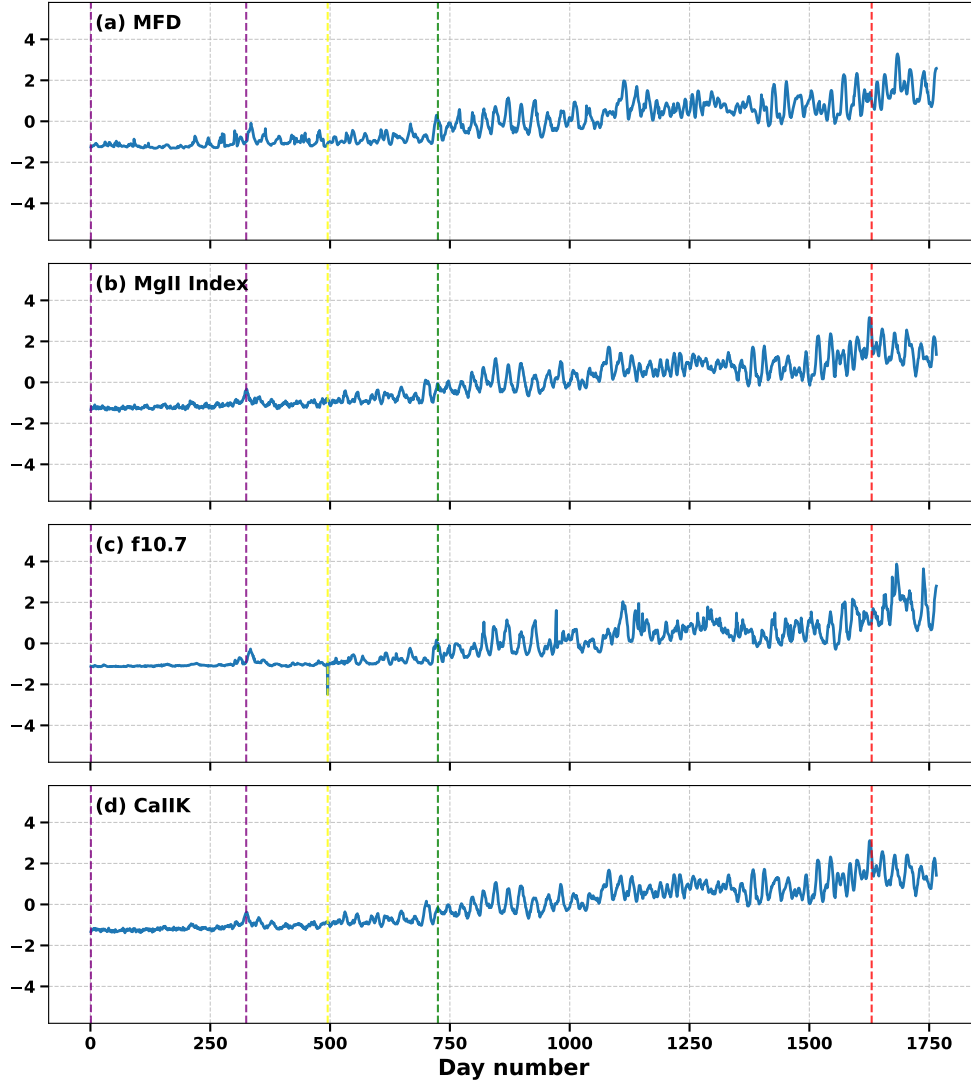


Fig. 1 Daily values of weak MFD computed with flux threshold panel (a), and the solar activity proxies: MgII index, f10.7cm, and Ca II K indicated in panels (b) to (d), respectively, from the ascending phase of Solar Cycle 25'.

Pearson and Spearman Correlations

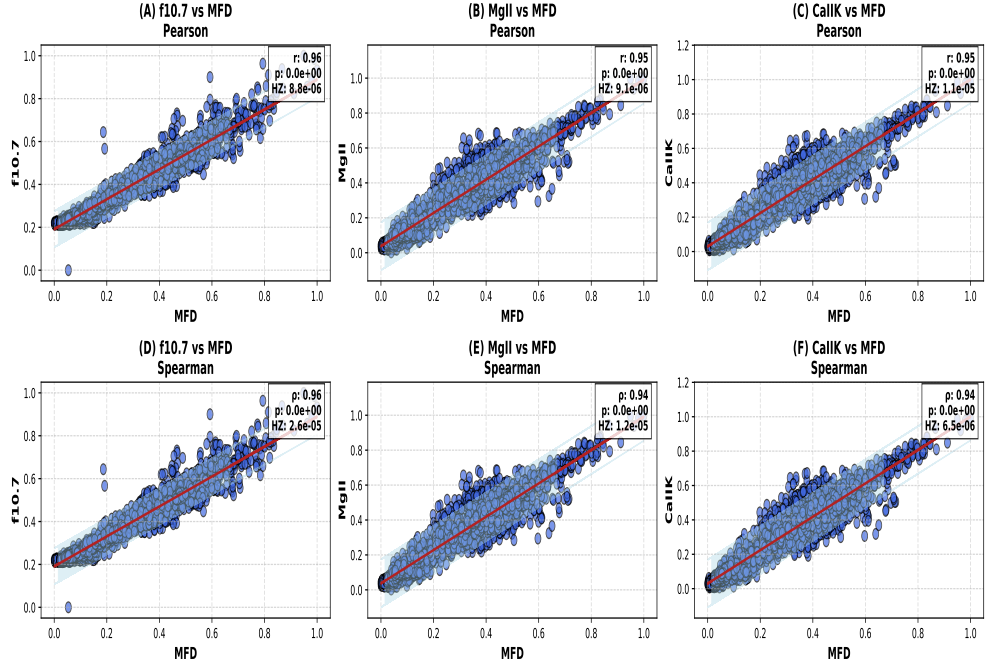


Fig. 2 The Pearson and Spearman correlation analysis results at lag 0 between weak magnetic flux density (MFD) and key solar activity proxies, the upper three panels and the lower three panels, respectively. The 95% bootstrapped CI is indicated as water shaded areas between the data sets. .

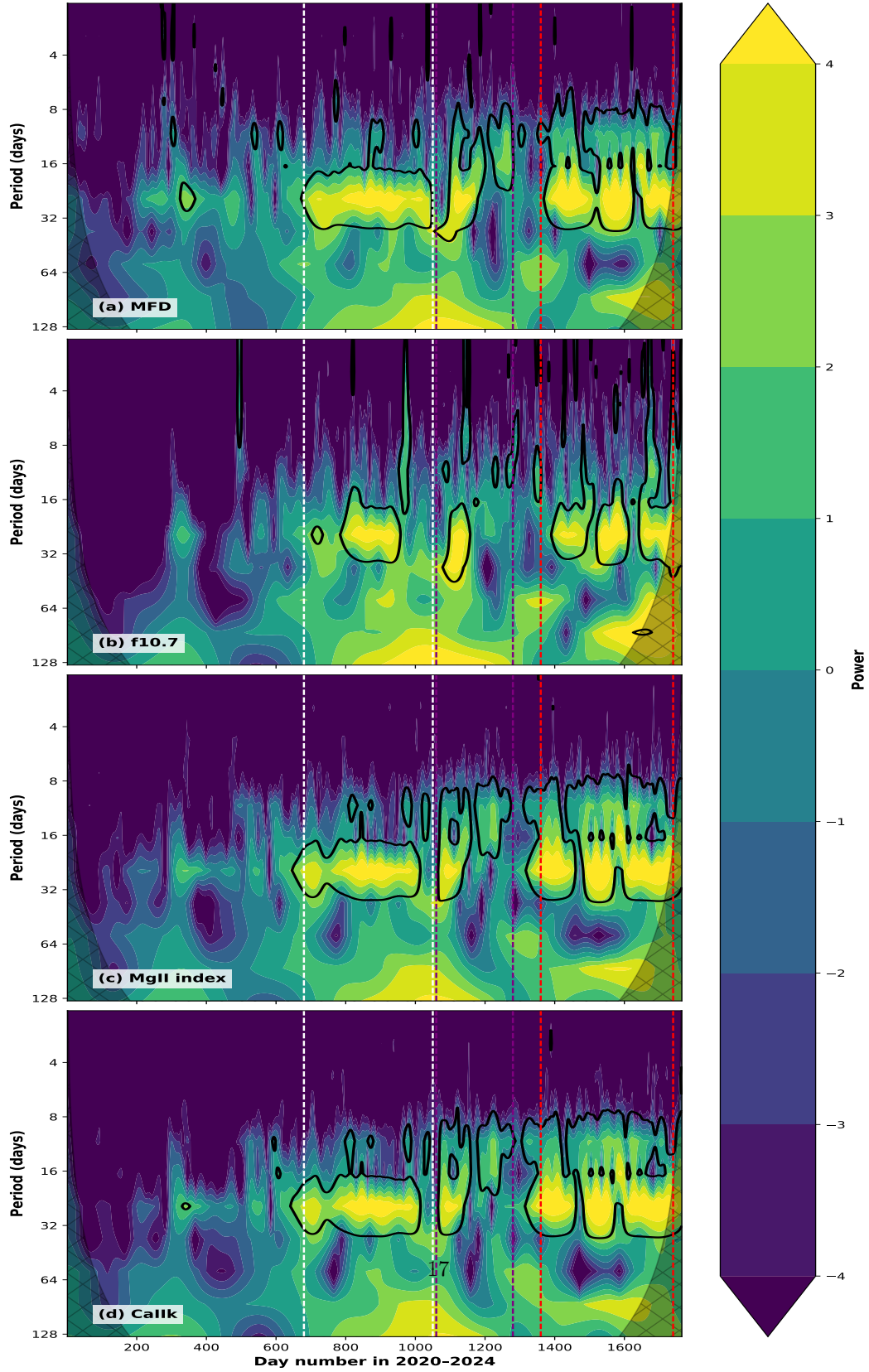


Fig. 3 Continuous Wavelet Transform (CWT) results for the data sets in the year 2020-2024 of magnetic flux density (MFD) panel (a), and solar activity proxies: f10.7 cm radio flux, Mg II index and Ca II K from panel (b) to (d), respectively. The lighter shaded region represents the cone of influence (COI), where edge effects may influence the reliability of the results, while the thick contour denotes the 95 % confidence interval (CI), determined using the Monte Carlo method.

Cross-Correlation Analysis: Solar Proxies vs Magnetic Flux Density

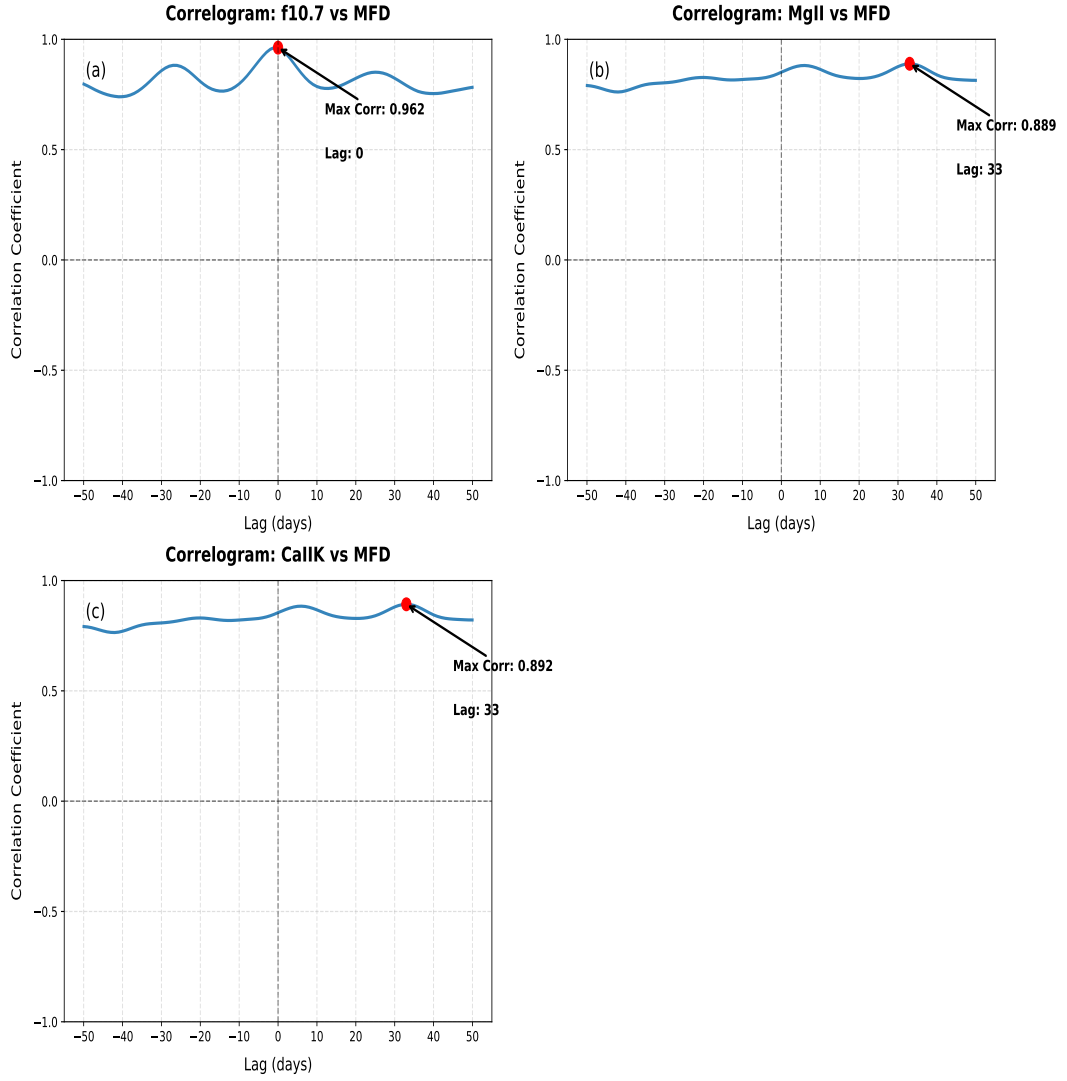


Fig. 4 The Cross-Correlogram between f10.7 cm and MFD panel (a), Mg II and MFD panel (b), and Ca II K and MFD panel (C) in the year 2020 to 2024.

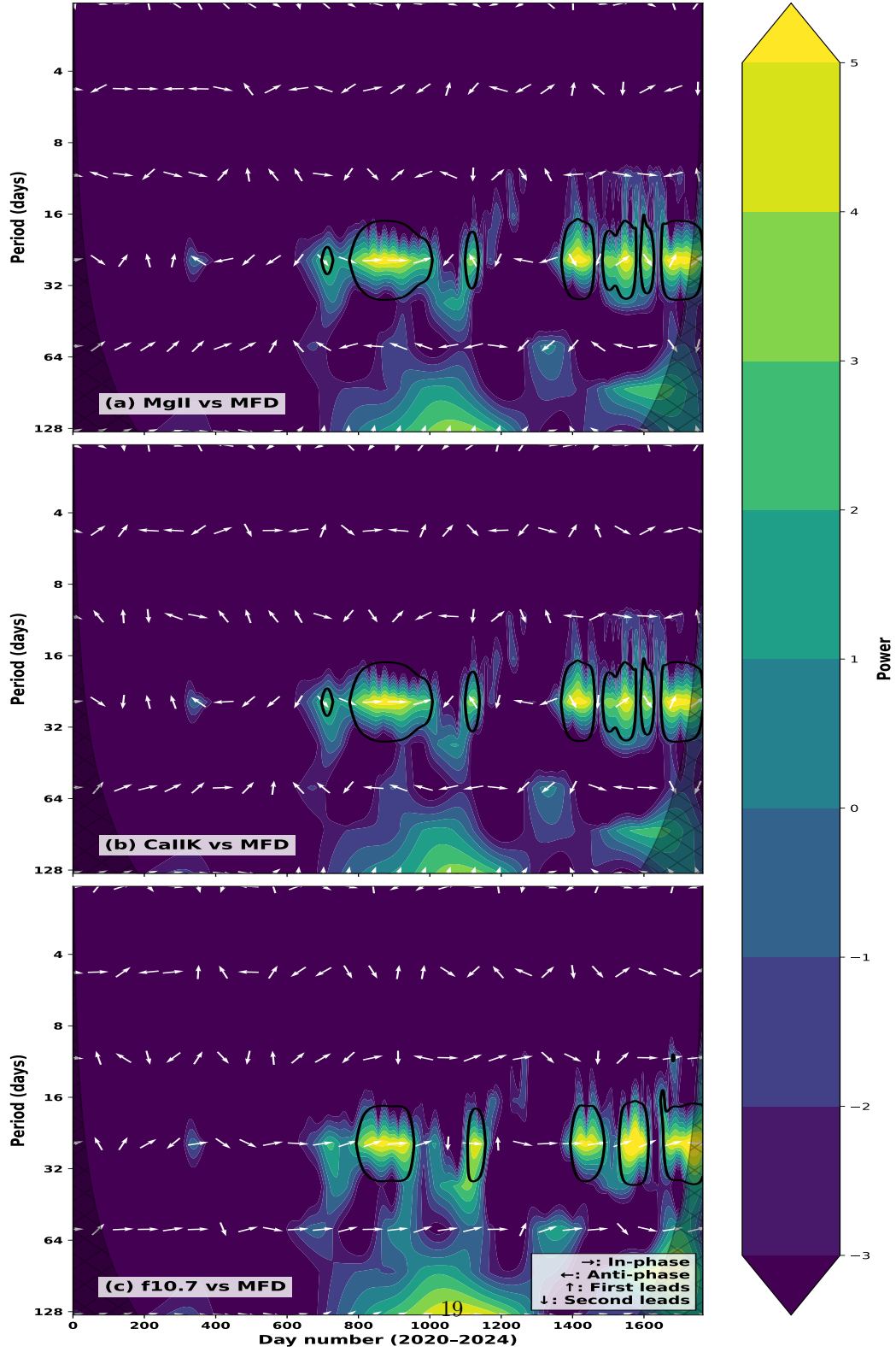


Fig. 5 Cross-wavelet transform (XWT) between magnetic flux density (MFD) and key solar activity proxies: F10.7 cm radio flux, Mg II index, and Ca II K-line. Arrows pointing to the right indicate in-phase behavior, while arrows pointing to the left indicate anti-phase behavior. Arrows pointing upward (90°) indicate that the first series leads, whereas arrows pointing downward (90°) indicate that the second series leads.