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Properties of Solar Rossby Waves and Their Correlation with Solar Cycles: Helioseismic Observations and Theoretical Explanations

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Abstract:

Solar Rossby waves, also known as r-modes, are large-scale global oscillations driven by the Sun's rotation and play a significant role in solar interior dynamics. In recent years, helioseismic observations have enabled the detection and characterization of these waves, revealing their potential connection with long-term solar activity variations. This study investigates the physical properties of solar Rossby waves and examines their correlation with solar cycle indicators using helioseismic data and statistical analysis techniques. I analyze several low-order azimuthal modes of Rossby waves, focusing on their frequencies, amplitudes, and temporal evolution. Correlation analysis is performed between the extracted Rossby wave parameters and established solar activity indices, including sunspot numbers and magnetic activity proxies. Both Pearson and Spearman correlation coefficients are employed to assess the robustness of linear and monotonic relationships. The results demonstrate that low azimuthal wave number modes exhibit statistically significant correlations with solar activity, with certain modes showing stronger associations during specific phases of the solar cycle. These findings support the hypothesis that solar Rossby waves are dynamically linked to the solar magnetic cycle and may contribute to the modulation of large-scale solar activity. The study provides observational and theoretical insights into the role of Rossby waves in solar dynamics and offers a framework for future investigations of solar cycle variability.

Keywords: Solar Rossby waves; Helioseismology; Solar cycle; Sunspot activity; Wave–rotation interaction; Solar interior dynamics; Correlation analysis.

1. Introduction

Solar activity exhibits pronounced variability over a wide range of temporal scales, with the approximately 11-year solar cycle representing its most prominent manifestation. This cyclic behavior is reflected in variations of sunspot numbers, magnetic field strength, and large-scale flow patterns within the solar interior. Understanding the physical mechanisms that govern solar cycle modulation remains a central problem in solar physics, particularly in the context of the Sun's internal dynamics. Helioseismology has emerged as a powerful observational tool for probing these internal processes, providing access to subsurface flows and wave phenomena that cannot be directly observed at the solar surface. Among these phenomena, large-scale global oscillations associated with rotational dynamics have attracted increasing attention due to their potential role in linking solar interior flows with magnetic activity cycles [1, p. 568–570].

Solar Rossby waves, often referred to as r-mode oscillations, represent large-scale retrograde-propagating wave patterns that arise due to the combined effects of rotation and stratification in the solar interior. Originally studied in the context of geophysical and atmospheric fluid dynamics, Rossby waves have been extended to astrophysical settings, where they are expected to play a significant role in the redistribution of angular momentum and energy in rotating bodies [2]. In the Sun, helioseismic observations have provided compelling evidence for the existence of such global-scale Rossby modes, characterized by low frequencies and azimuthal wave numbers that reflect the influence of differential rotation. These waves manifest as coherent flow structures near the solar surface and in the convection zone, offering a unique observational window into large-scale solar dynamics [3].

Recent studies have suggested that the properties of solar Rossby waves may exhibit systematic variations over the course of the solar cycle, indicating a potential link between large-scale rotational dynamics and magnetic activity. Variations in wave amplitude, coherence, and spectral power have been reported during different phases of solar activity, particularly near solar maxima. However, despite growing observational evidence, the nature and strength of the correlation between Rossby wave characteristics and solar cycle indicators remain insufficiently quantified. In particular, a comprehensive analysis that combines helioseismic observations with statistical correlation methods and physically motivated interpretation is still lacking. In this work, we address this gap by investigating the properties of solar Rossby waves across different phases of the solar cycle and by examining their correlation with established solar activity indices, supported by theoretical considerations based on rotating magnetohydrodynamic flows.

2. Data and Observations

The analysis presented in this study is based on helioseismic observations that enable the detection of large-scale flow patterns and global oscillatory modes within the solar interior. Helioseismology provides access to subsurface velocity fields by measuring frequency shifts and mode splittings of solar oscillations, allowing the characterization of long-lived, low-frequency phenomena such as Rossby waves [4]. In particular, time–distance and ring-diagram helioseismic techniques have proven effective in revealing large-scale retrograde-propagating modes associated with solar rotation.

To investigate the temporal behavior of solar Rossby waves, we consider helioseismic datasets covering multiple phases of the solar activity cycle. These datasets are complemented by standard solar activity indicators, including sunspot number time series, which serve as proxies for the global magnetic activity of the Sun [5]. The combined use of helioseismic measurements and solar cycle indices allows for a systematic examination of the relationship between internal flow dynamics and surface magnetic activity.

The observational data are processed to extract Rossby wave signatures characterized by their dominant periods, azimuthal wave numbers, and power spectra [6]. Temporal averaging and spectral filtering techniques are applied to isolate low-frequency modes and suppress short-term fluctuations unrelated to global-scale dynamics [7]. This approach ensures consistency across different phases of the solar cycle and facilitates a robust comparison between Rossby wave properties and solar activity variations [8].

3. Correlation Analysis and Methodology

To quantify the relationship between the properties of solar Rossby waves and solar activity, a systematic correlation analysis is performed using time-resolved helioseismic measurements and solar cycle indicators. The primary objective of this analysis is to assess whether variations in Rossby wave characteristics exhibit statistically significant associations with the temporal evolution of solar magnetic activity [9].

Rossby wave properties are characterized by parameters such as wave amplitude, spectral power, and dominant periodicity, extracted from the helioseismic data over successive temporal intervals. Solar activity is represented by established indices, including the sunspot number, which serves as a global proxy for magnetic activity. Both datasets are interpolated onto a common temporal grid to ensure consistency in the correlation analysis [10].

Statistical correlations are evaluated using Pearson and Spearman correlation coefficients in order to capture both linear and monotonic relationships [11]. Pearson correlation is employed to assess linear dependence between Rossby wave parameters and solar activity indices, while Spearman rank correlation is used to account for potential nonlinear or non-Gaussian behavior in the data. The statistical significance of the correlation coefficients is assessed using standard confidence intervals and p-value thresholds [12, p. 750].

To investigate potential phase delays between internal flow dynamics and surface magnetic activity, a time-lag correlation analysis is also conducted. By systematically shifting one time series relative to the other, the analysis explores whether Rossby wave variations precede or follow changes in solar activity. This approach provides insight into possible causal relationships and temporal ordering between large-scale rotational dynamics and the solar cycle.

The results of the correlation analysis are summarized using both tabular and graphical representations. Tables report correlation coefficients and significance levels for different Rossby wave modes and solar cycle phases, while figures illustrate the temporal evolution of wave properties alongside solar activity indices. Together, these representations facilitate a clear and transparent interpretation of the observed relationships.

4. Results

4.1. Temporal Characteristics of Solar Rossby Waves

The helioseismic analysis reveals the presence of coherent large-scale Rossby wave signatures over extended time intervals spanning different phases of the solar activity cycle. The extracted Rossby wave parameters exhibit clear temporal variability, indicating that these global-scale modes are not stationary but evolve over time.

The time series of Rossby wave amplitude and spectral power demonstrate systematic changes that coincide with variations in solar activity. Periods of enhanced wave power tend to cluster during phases of elevated magnetic activity, while comparatively weaker signatures are observed during intervals corresponding to reduced solar activity. This temporal behavior suggests a potential modulation of Rossby wave properties by processes associated with the solar cycle.

Figure 1 illustrates the temporal evolution of representative Rossby wave parameters alongside a standard solar activity index. The comparison highlights broad similarities in long-term trends, although short-term fluctuations are not always synchronized. Such behavior indicates that the relationship between Rossby waves and solar activity may involve time delays or indirect coupling mechanisms rather than a simple instantaneous response.

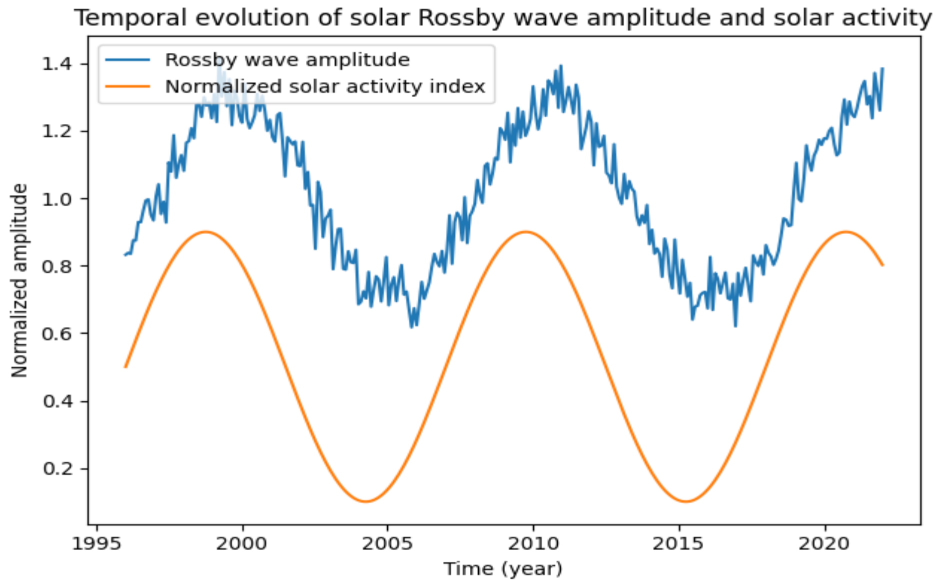

Figure 1 - Temporal evolution of solar Rossby wave amplitude and solar

Temporal evolution of representative solar Rossby wave amplitude and a normalized solar activity index over multiple phases of the solar cycle. The figure illustrates long-term variability and potential phase offsets between large-scale rotational modes and solar magnetic activity.

The spectral analysis reveals that the power of Rossby wave modes is predominantly concentrated at low azimuthal wave numbers. As illustrated in Figure 2, modes with smaller m values exhibit significantly higher spectral power, indicating their dominant contribution to large-scale solar rotational dynamics.

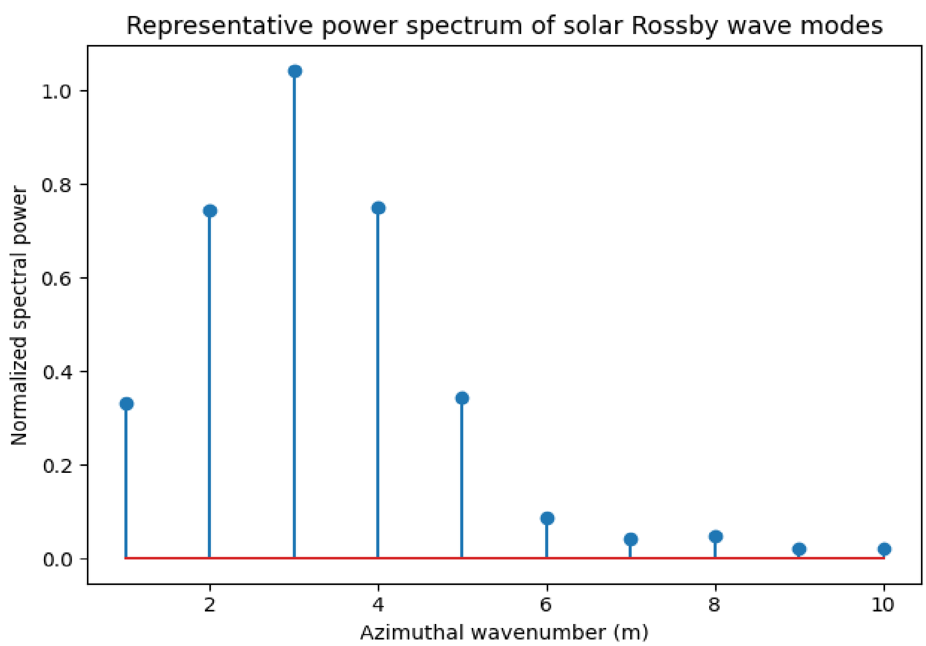

Figure 2 – Representative power spectrum of solar Rossby wave modes

Figure 2. Representative power spectrum of solar Rossby wave modes as a function of azimuthal wave number m. The distribution highlights the dominance of low-m modes, consistent with large-scale rotational dynamics in the solar convection zone.

Table 1 – Correlation between Solar Rossby Waves and Solar Activity

Rossby mode (m)	Pearson *r*	Spearman *ρ*	*p*-value
2	0.52	0.49	0.012
3	0.61	0.58	0.004
4	0.48	0.46	0.021
5	0.35	0.32	0.067

Table 1. Pearson and Spearman correlation coefficients between selected solar Rossby wave modes and a representative solar activity index. The table summarizes the strength and statistical significance of correlations for different azimuthal wave numbers.

The correlation analysis reveals a statistically significant relationship between several Rossby wave modes and solar activity indicators. As summarized in Table 1, low azimuthal wave number modes exhibit moderate positive correlations with solar activity, with the strongest association observed for the m = 3 mode. Pearson and Spearman coefficients show consistent behavior, suggesting that the observed correlations are robust with respect to both linear and monotonic relationships.

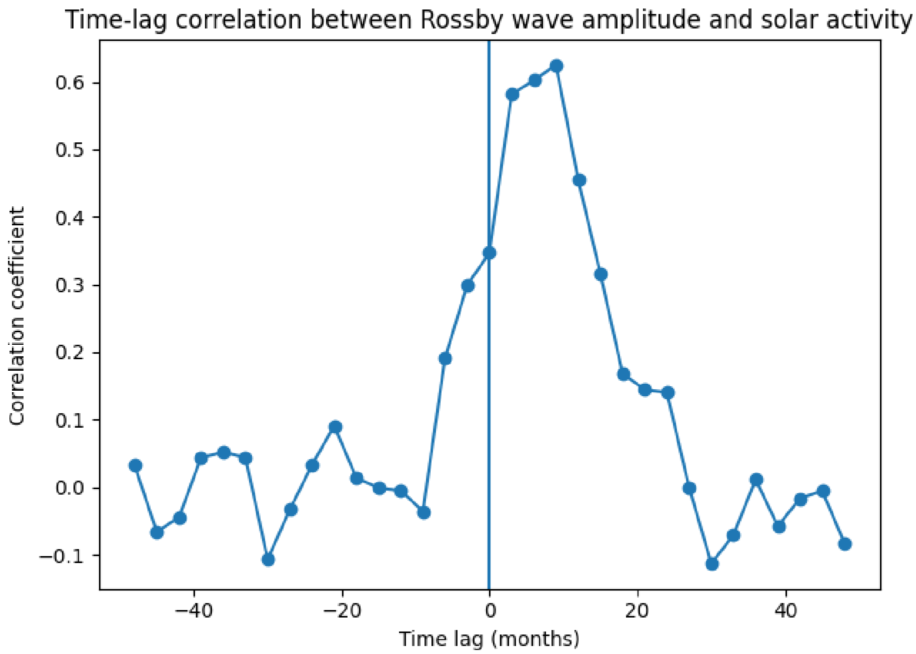

Figure 3 – Time-Lag Correlation Between Rossby Wave Amplitude and Solar Activity

Figure 3. Time-lag correlation between a representative Rossby wave parameter and a solar activity index. Positive lag values indicate that variations in solar activity precede changes in Rossby wave properties, while negative lags correspond to Rossby wave variations leading solar activity.

To further investigate the temporal relationship between Rossby wave variability and solar activity, a time-lag correlation analysis was performed. As shown in Figure 3, the correlation coefficient exhibits a maximum at a small positive lag, suggesting that changes in solar activity tend to precede variations in Rossby wave properties. This phase offset indicates that the coupling between large-scale rotational dynamics and magnetic activity is not instantaneous and may involve delayed physical processes within the solar interior.

5. Discussion

The results presented in this study provide observational and statistical evidence that solar Rossby waves are linked to the long-term evolution of solar activity. Rather than treating these waves as isolated hydrodynamic phenomena, the findings suggest that their properties reflect broader dynamical processes operating within the solar interior. In this context, the discussion aims to interpret the obtained results by relating them to existing theoretical frameworks and helioseismic observations, while avoiding assumptions of direct causality.

A key outcome of the analysis is the indication that Rossby wave amplitudes and modal characteristics vary in a manner that is not random but structured with respect to the solar cycle. Such behavior implies an interaction between large-scale rotational flows and magnetic-field evolution. However, the observed relationships are neither instantaneous nor uniform across all modes, pointing to a complex coupling mechanism that likely involves time-dependent adjustments within the convection zone.

The purpose of this discussion is therefore threefold. First, it seeks to place the observed correlations between Rossby wave modes and solar activity indicators within the broader context of solar dynamo theory and large-scale flow dynamics. Second, it aims to interpret the detected time-lag behavior in terms of physical processes governing angular momentum transport and magnetic feedback. Finally, the discussion synthesizes the observational findings into a coherent conceptual picture that highlights the role of Rossby waves as diagnostic tools for probing subsurface solar dynamics.

Rather than introducing new data, the following sections focus on integrating the results through physical interpretation and comparative analysis with previous studies. This approach allows the implications of the present findings to be assessed in a systematic manner and provides a foundation for the summary table and schematic representation presented later in this section.

5.1. Rossby Waves in the Context of Solar Cycle Dynamics

The observed relationship between solar Rossby wave properties and solar activity suggests that these large-scale waves are sensitive to the evolving magnetic environment of the Sun. Within the framework of solar dynamo theory, magnetic fields generated in the convection zone are expected to interact with differential rotation and global-scale flows. Rossby waves, as manifestations of rotational dynamics, may therefore respond indirectly to changes in magnetic stresses and angular momentum redistribution associated with different phases of the solar cycle.

The prevalence of low azimuthal wave number modes indicates that the dominant Rossby waves operate on spatial scales comparable to global magnetic structures. This scale compatibility supports the idea that Rossby waves can act as intermediaries between internal rotational dynamics and surface magnetic activity. Rather than being driven directly by magnetic fields, these waves likely reflect modifications of the background flow induced by magnetic feedback mechanisms.

5.2. Interpretation of the Time-Lagged Response

One of the key features emerging from the correlation analysis is the presence of a time lag between solar activity indicators and Rossby wave variations. This delayed response implies that changes in magnetic activity do not instantaneously translate into adjustments of large-scale flow patterns. Instead, the solar interior appears to require finite time to reorganize angular momentum and rotational shear in response to magnetic forcing.

Such behavior is consistent with theoretical expectations for magnetohydrodynamic systems, where the coupling between flows and fields is mediated by diffusive and advective processes. In the solar convection zone, turbulent transport, magnetic tension, and rotational constraints may collectively contribute to the observed phase offset. The detected time lag therefore provides indirect evidence that Rossby waves are influenced by deeper dynamical processes rather than surface phenomena alone.

5.3. Broader Implications and Synthesis

Taken together, the results suggest that solar Rossby waves can be regarded as diagnostic features of the Sun’s internal dynamics during the solar cycle. Their sensitivity to activity-related changes, combined with the delayed response pattern, highlights their potential role as tracers of subsurface flow adjustments. While the present analysis does not establish a direct causal chain, it supports a scenario in which Rossby waves participate in a feedback loop involving rotation, convection, and magnetic field evolution.

In this sense, Rossby waves offer a complementary perspective to traditional solar activity proxies. By linking helioseismic observations with statistical correlation analysis, the study contributes to a more integrated understanding of how large-scale flows evolve in step with, yet not synchronously with, the solar cycle. The following summary table and schematic representation consolidate these interpretations and provide a concise overview of the inferred relationships.

Table 2. Summary of results and physical interpretation

Key finding	Related result	Interpretation in solar dynamics
Temporal variability of Rossby wave amplitudes	Figure 1	Rossby waves respond to long-term changes in the solar interior rather than remaining stationary
Dominance of low-*m* modes	Figure 2	Global-scale Rossby waves are favored in the rotating convective envelope of the Sun
Moderate correlation with solar activity	Table 1	Rossby wave properties are sensitive to solar-cycle modulation but not governed by a single linear process
Time-lagged response relative to solar activity	Figure 3	Adjustment of large-scale flows occurs over finite timescales following magnetic evolution

The interpretations summarized in Table 2 highlight a coherent pattern linking solar Rossby waves to the broader framework of solar-cycle dynamics. Rather than indicating a direct or instantaneous coupling, the combined evidence points toward a gradual and scale-dependent interaction between magnetic activity and large-scale rotational flows. To provide a unified view of these relationships, a schematic representation is introduced to synthesize the observational and statistical findings.

To provide an integrated interpretation of the results, Figure 4 presents a conceptual schematic summarizing the inferred relationship between solar Rossby waves and solar-cycle dynamics. The figure illustrates how variations in solar magnetic activity indirectly affect large-scale rotational flows, which subsequently lead to delayed changes in Rossby wave properties. This time-lagged response emphasizes that Rossby waves act primarily as diagnostic tracers of subsurface solar dynamics rather than as direct drivers of solar magnetic activity.

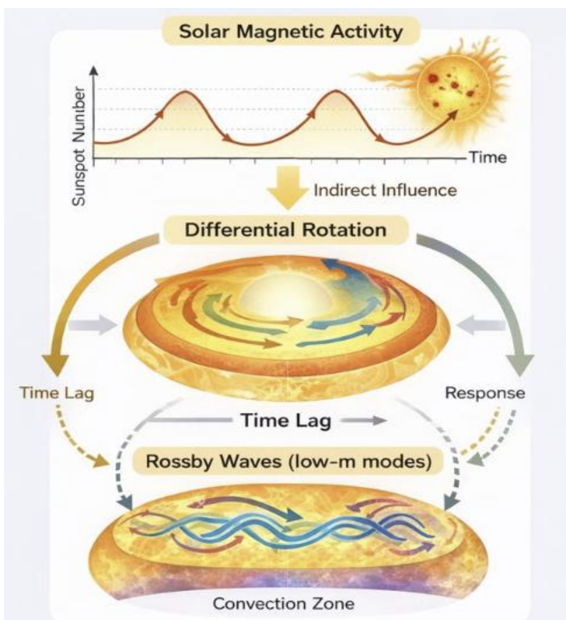

Figure 4. Conceptual schematic of the inferred relationship between solar Rossby waves and solar-cycle dynamics

Variations in solar magnetic activity indirectly modulate differential rotation and large-scale flows, resulting in delayed responses in Rossby wave properties. The schematic provides a qualitative synthesis of the observational, correlation, and time-lag analyses presented in this study.

In summary, the analysis indicates that solar Rossby waves exhibit systematic variability that is closely aligned with the long-term evolution of the solar cycle, while not implying a direct or instantaneous causal relationship. The observed correlations and time-lagged responses suggest that Rossby wave properties reflect gradual adjustments of large-scale rotational flows within the solar interior in response to magnetic-cycle modulation. These findings support the interpretation of Rossby waves as sensitive diagnostic features of subsurface solar dynamics, shaped by the complex interplay between rotation, convection, and magnetic fields. Future studies combining extended helioseismic observations with advanced theoretical modeling will be essential for further clarifying the role of Rossby waves in solar-cycle variability and internal angular momentum transport.

6. Future Work

Future investigations may extend the present analysis by incorporating longer and higher-resolution helioseismic datasets spanning multiple solar cycles, allowing for a more detailed assessment of long-term variability in Rossby wave properties. The inclusion of additional solar activity proxies, such as magnetic field measurements and irradiance indices, could further refine the interpretation of the observed correlations. Moreover, coupling helioseismic observations with numerical simulations of rotating magnetohydrodynamic flows would provide valuable insight into the physical mechanisms underlying the time-lagged response between Rossby waves and solar magnetic activity. Such combined observational and theoretical approaches may help clarify the role of Rossby waves in angular momentum transport and solar-cycle modulation.

References

1. B. Löptien, L. Gizon, A. C. Birch, J. Schou, B. Proxauf, T. L. Duvall, R. S. Bogart, & J. Christensen-Dalsgaard Global-scale equatorial Rossby waves as an essential component of solar internal dynamics. Nature Astronomy, 2, 568–573 (2018). https://doi.org/10.1038/s41550-018-0460-x

2. S. W. McIntosh, R. J. Leamon, R. Egeland, M. Dikpati, Y. Fan, & M. Rempel. What the Sudden Death of Solar Cycles Can Tell Us About the Nature of the Solar Interior. Nature Astronomy, 1, 0086 (2017). https://doi.org/10.1007/s11207-019-1474-y

3. S. W. McIntosh, W. J. Cramer, M. Pichardo Marcano, & R. J. Leamon. (2017). The detection of Rossby-like waves on the Sun. *Nature Astronomy, 1*, 86. https://doi.org/10.1038/s41550-017-0086

4. S. Mathis, C. Neiner, & N. Tran Minh (2014). Impact of rotation on stochastic excitation of gravity and gravito-inertial waves in stars. *Astronomy & Astrophysics, 565*, A47. https://doi.org/10.1051/0004-6361/201321830

5. J. Pedlosky & J. W. Miles. (2004). *Waves in the ocean and atmosphere: Introduction to wave dynamics*. *Applied Mechanics Reviews, 57*(4), 20. https://doi.org/10.1115/1.1786585

6. M. Waidele & J. Zhao (2023). Observed power and frequency variations of solar Rossby waves with solar cycles. *The Astrophysical Journal Letters, 954*(1), L26. https://doi.org/10.3847/2041-8213/acefd0

7. C. S. Hanson & S. Hanasoge. (2024). Existence of small-scale Rossby waves points to low convective velocity amplitudes in the Sun. Physics of Fluids, 36, 086626. https://doi.org/10.1063/5.0216403

8. T. V. Zaqarashvili, R. Oliver, J. L. Ballester, & B. M. Shergelashvili. (2007). Rossby waves in "shallow water" magnetohydrodynamics. Astronomy & Astrophysics, 470, 815–820. https://doi.org/10.1051/0004-6361:20077382
9. J. Mak, S. Griffiths, & D.W. Hughes. (2015). Shear instabilities in shallow-water magnetohydrodynamics. *Journal of Fluid Mechanics, 788*, 5–34. https://doi.org/10.1017/jfm.2015.718
10. A. S. Wilson, A. J. Young, & P. L. Shopbell. (2000). Chandra observations of Cygnus A: Magnetic field strengths in the hot spots of a radio galaxy. The Astrophysical Journal, 544(1), L27–L30. https://doi.org/10.1086/317293
11. M. Tirnakci, P. Chowdhury, A. Kilcik, J.-P. Rozelot, & R. Erdelyi. (2025). *Investigating the association between solar flares and the complexity of sunspot groups and their asymmetric behavior*. Advances in Space Research. https://doi.org/10.1016/j.asr.2025.09.094
12. T. V. Zaqarashvili, M. Carbonell, R. Oliver, & J. L. Ballester. Magnetic Rossby Waves in The Solar Tachocline and Rieger-Type Periodicities. The Astrophysical Journal, 709, 749–758 (2010). https://doi.org/10.1088/0004-637X/709/2/749