

Analyzing the relationship between solar magnetic polarity, solar wind velocity, and vertical magnetic field (Bz)

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(Received: 29 April 2024, Accepted: 29 July 2024)

Abstract

This study examines the influence of solar magnetic polarity and solar wind velocity on the Bz-component of the interplanetary magnetic field (IMF Bz) during the solar cycles 22, 23, 24, and 25, characterized by the minimum of solar activity. The analysis reveals a distinctive pattern in the behavior of the solar magnetic field. Specifically, during even solar cycles (22 and 24), the solar magnetic field exhibits an opposite polarity, while in odd solar cycles (23 and 25), it demonstrates a positive polarity. This finding supports the formulation of an odd-even hypothesis, which is further corroborated by the qualitative analysis of IMF Bz to other factors such as IMF Bx, solar wind velocity, and the polarity of the Sun's magnetic field. Our investigation reveals that IMF Bz is significantly influenced by the polarity of the Sun's magnetic field, solar wind velocity, and the magnitude of the IMF horizontal component (Bx). Moreover, we find a positive correlation between IMF Bz and both Bx and solar wind velocity, regardless of the magnetic field polarity being positive or negative. These findings contribute to our understanding of the interplay between solar magnetic activity, solar wind dynamics, and the behavior of the interplanetary magnetic field during periods of minimum solar activity. The dependencies observed in this study offer valuable insights into the complex nature of solar-terrestrial interactions. Furthermore, they hold implications for studying the effects of solar variability on Earth's magnetosphere. By comprehending the relationships between solar magnetic activity, solar wind properties, and the behavior of the interplanetary magnetic field, scientists can gain a deeper understanding of the dynamics involved in the interaction between the Sun and the Earth's magnetic field. This research sheds light on the factors influencing the IMF Bz and provides a foundation for further investigations in this field. With the continuously advancing knowledge in solar physics and space weather, these findings contribute to the broader scientific understanding of our solar system and its effects on our planet. Further studies building upon these insights may aid in predicting and mitigating the potential impacts of solar variability on various technological systems and the Earth's space environment. This study contributes to the scientific understanding of the influence of solar magnetic polarity and solar wind velocity on the interplanetary magnetic field. The observed patterns and correlations provide valuable insights into the dynamics of solar-terrestrial interactions, paving the way for further research in the field of space weather and its impacts on Earth.

Keywords: Solar wind velocity, interplanetary magnetic field, magnetic polarity, solar cycle

1 Introduction

The Sun, our closest star, has long been a subject of intense study due to its vital role in the dynamics of our solar system. Among the various aspects of solar activity, the interplanetary magnetic field (IMF) plays a crucial role in shaping the behavior of the solar wind and its interaction with the Earth's magnetosphere. Understanding the factors that influence the IMF, particularly its component along the z-axis (B_z), is essential for unraveling the complex dynamics of the Sun-Earth system. Previous research has shed light on the correlation between the IMF B_z and the interplanetary magnetic field's horizontal component (IMF B_x) as well as the polarity of the Sun's magnetic field. Lyatsky et al. (2003) conducted a notable study investigating this relationship during the minimum periods of four solar cycles: 21, 22, 23, and 24. Their findings suggested a significant dependence of IMF B_z on IMF B_x and the solar magnetic polarity during these solar activity minima. In light of these previous findings, our research aims to further explore the influence of solar magnetic polarity and solar wind velocity on the IMF B_z . We extend the investigation to include additional solar cycles and periods of minimum solar activity, namely cycles 22 to 25 spanning the years 1986 to 2022. By conducting a statistical analysis of IMF B_z during these cycles, we aim to contribute to the understanding of the interplay between the IMF, solar wind dynamics, and various solar and geomagnetic parameters. In this research article, we present the results obtained from our analysis and compare them with the findings of Lyatsky et al. (2003). These results suggest that there is a dependency of IMF B_z on IMF B_x and solar magnetic polarity during solar activity minima. By examining the relationship between IMF B_z , IMF B_x , solar magnetic polarity, and solar wind

velocity, we aim to provide further insights into the complex dynamics of the interplanetary magnetic field and its interactions with the Sun and Earth. These findings have implications for understanding solar-terrestrial interactions, magnetospheric dynamics, and cosmic ray phenomena.

The interplanetary magnetic field (IMF) originates from the Sun and extends into interplanetary space [Kyung-Eun Cho et al., 2019; Velli et al., 1997; Dessler et al., 1967; Russell et al., 1974]. The IMF has three components, with the B_x and B_y axes being parallel to the ecliptic plane. The third component, known as the B_z value, is perpendicular to the ecliptic and is influenced by the solar wind's waves and other disturbances [Takao Aoki et al., 2006; Pizzo, V.J. et al., 1994; Howard et al., 1972]. The strength and direction of the geosynchronous magnetic field are significantly affected by the solar wind and the interplanetary magnetic field [Simon Wing et al., 1997; Antonucci et al., 1974; Fougere et al., 1974]. While the behavior of the IMF's horizontal components has been extensively studied, the research on the behavior of the IMF's B_z component, which is crucial for geomagnetic activity, is relatively limited [Gonzalez, W. D et al., 1987; Kamide, Y. et al., 1998; Babcock, H. D et al., 1959; Hirshberg et al., 1969]. Moreover, no definitive dependencies of IMF B_z on the Sun's magnetic field polarity have been found. The interplanetary magnetic field lines that originate from the Sun are continuously swept away by the solar wind and solar cosmic rays [Barker et al., 1971; Gazis P.R. et al., 1997; Jokipii et al., 1971]. Understanding the IMF is essential for comprehending the physics of solar-terrestrial interactions, the magnetosphere, and cosmic rays. In 1963-1964, the IMP-1 satellite provided the initial set of data on the IMF, and since then, numerous publications on this topic have been released [Tritakis, 1979;

Ponyavin, D. I. et al., 1991; Hirshberg et al., 1968]. The correlation between the IMF's horizontal components and the solar magnetic field has long been established [Gosling et al., 1993, 1997; Crooker et al., 1997; Berti et al., 2006]. The solar wind comprises a constant, slow component, and a variable, fast component that can reach speeds of up to 800 km/s. The slow component is believed to originate from elongated structures near the solar equator, which extend over the arched magnetic fields of the streamer belt. During periods of high solar activity, fast wind emerges from the polar regions of the Sun within the open magnetic field line regions known as polar holes. Conversely, the slow wind is observed in the equatorial plane and is associated with "helmet"-shaped coronal structures containing closed magnetic field lines. The solar activity cycle's minimum phase significantly alters this configuration, as the polar coronal holes, prominent during high activity, become less visible in the equatorial regions [Forsyth et al., 1997; Forsyth and Breen, 2002; Balogh et al., 1999; Wilcox et al., 1972; King et al., 1976]. The fast wind, present in isolated areas of open field lines covering most of the solar surface and in coronal holes near the poles, allows hot gas to escape freely [Rosenberg, R.L, et al., 1969; Smith et al., 1973]. Overall, this study contributes to the growing body of research aimed at unraveling the intricate connections between the Sun, solar wind, interplanetary magnetic field, and Earth's magnetosphere. By expanding our understanding of the factors influencing IMF Bz, we can enhance our knowledge of space weather phenomena and their potential impacts on technological systems and space exploration.

This research aims to perform a statistical analysis of the IMF Bz component during four solar cycles (SC 22 to SC 25) corresponding to the years 1986-1988, 1996-1998, 2009-2011, and

2020-2022, which represent periods of minimum solar activity. In this study, we consider the IMF Bz's dependence on the IMF horizontal component Bx, the solar wind velocity, and the polarity of the Sun's magnetic field. This research seeks to contribute to the understanding of the interplay between the interplanetary magnetic field and various solar and geomagnetic parameters during periods of minimum solar activity, shedding light on the complex dynamics of the Sun-Earth system.

2 Data Used for the Analysis:

During the analysis, data from the interplanetary magnetic field (IMF) and solar wind velocity were collected by the VOYAGER-II spacecraft. The VOYAGER-II spacecraft, launched in 1977 as a NASA mission to study the outer planets of our solar system, provides invaluable data on the interplanetary magnetic field and solar wind properties, which are crucial for understanding space weather and solar-terrestrial interactions. The spacecraft is equipped with a suite of instruments designed to measure various parameters of the solar wind, including the interplanetary magnetic field. These instruments enable the collection of high-resolution and high-precision data, offering important insights into the dynamics of the solar wind and its interaction with the interplanetary medium. In this study, hourly data from the VOYAGER-II spacecraft were utilized, covering four periods of minimum solar activity from 1986 to 1988, 1996 to 1998, 2009 to 2011, and 2020 to 2022. To ensure data quality and minimize the impact of erratic solar wind conditions, a filtering process was applied to the data. Occurrences with an IMF lower than 20 nT and a solar wind speed > 400 km/s were excluded from the analysis. These threshold values were selected based on the specific objectives and the characteristics of the phenomena under

investigation. It should be noted that the positions of the VOYAGER-II spacecraft during the considered periods are important since the interplanetary magnetic field measured by the spacecraft can depend on its distance from the Sun. The approximate positions of the spacecraft during each period were determined based on available trajectory information or orbital data. This consideration accounts for the varying distance from the Sun and helps contextualize the measurements. Regarding the IMF components, B_x represents the horizontal component perpendicular to the Sun-Earth line, whereas B_y represents the east-west component. The specific definitions and calculations of B_x and B_y can vary depending on the conventions or coordinate systems used in the study. It is important to provide a clear and concise definition of B_x and specify the coordinate system. By incorporating the positions of the VOYAGER-II spacecraft, the definitions of B_x and B_y , and a more detailed explanation of the filtering criteria, we aim to provide a comprehensive and accurate analysis of the relationship between IMF and solar wind velocity during periods of minimum solar activity.

3 Results and discussion

In this study, we aimed to investigate the influence of solar magnetic polarity on the interplanetary magnetic field (IMF) B_z during the minimum activity of solar cycles 22, 23, 24, and 25. Lyatsky et al. (2003) conducted a statistical analysis of the impact of solar magnetic polarity on IMF B_z during two solar minima: 1985–1987 and 1995–1997. Building upon their work, we extended the analysis to include the minimum periods of solar cycles 22, 23, 24, and 25. During periods of minimal solar activity, characterized by a low number of sunspots and generally quiet solar wind conditions, the polarity of the

solar magnetic field plays a crucial role. In our investigation, we classified the negative polarity of the solar magnetic field with field lines entering the northern hemisphere, while the positive polarity corresponds to field lines leaving the region. The observed consistent parabolic shape in the trend lines of all four solar cycles indicates a nonlinear relationship between IMF B_z and B_x during the minimum activity phases. This suggests that the interplay between these magnetic field components is complex and influenced by various factors. In Figure 1(a), the analysis of 3330 hourly measurements during the minimum of solar cycle 22 (1986–1988) revealed a negative polarity of the solar magnetic field. The equation $B_z = (0.2457) + 0.0152(B_x) - 0.0127(B_x)^2$ describes the relationship between IMF B_z and B_x during this period. The negative coefficient of the quadratic term (-0.0127) indicates that the relationship exhibits a concave shape, with IMF B_z decreasing as B_x increases. The calculated second derivative of the equation (B_z'') being -0.0254 further confirms the downward trend or negative curvature in the relationship between IMF B_z and B_x during the minimum of solar cycle 22. This provides additional evidence of the influence of the solar magnetic field polarity on the behavior of IMF B_z . Additionally, the strong correlation coefficient ($R = 0.87$) between IMF B_z and B_x during the minimum of solar cycle 22 indicates a significant relationship between these variables. This implies that changes in B_x are associated with corresponding changes in IMF B_z , further emphasizing the interdependence of these magnetic field components. In Figure 1(b), the analysis of 2662 hourly observations during the minimum of solar cycle 23 (1996–1998) revealed a positive polarity of the solar magnetic field. The equation $B_z = (-0.294) - 0.0189(B_x) + 0.019(B_x)^2$ describes the relationship

between IMF Bz and Bx during this period. The positive coefficient of the quadratic term (0.019) indicates a convex shape, with IMF Bz increasing as Bx increases. The relatively low correlation coefficient ($R = 0.128$) observed between IMF Bz and Bx during the minimum of

solar cycle 23 suggests a weaker relationship compared to the other solar cycles studied. This implies that other factors, such as solar wind variations or local magnetic field configurations, may have a more significant influence on IMF Bz during this particular period.

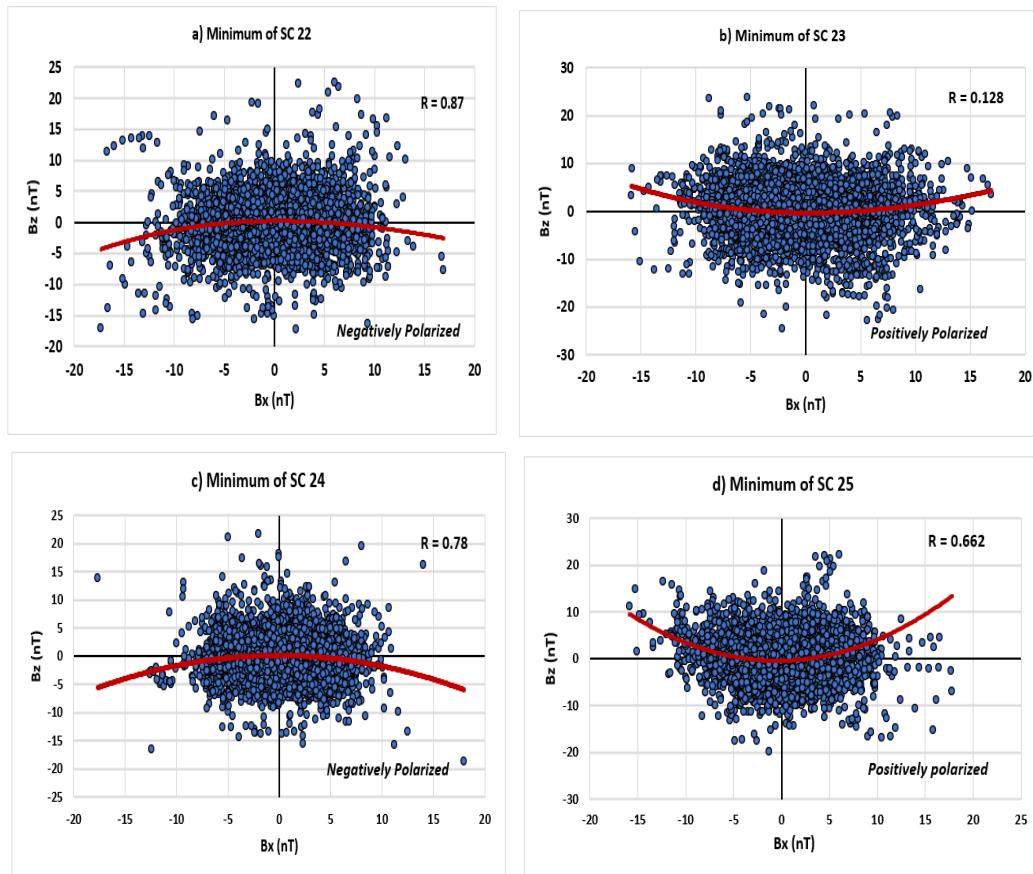


Figure 1. The dependence of IMF Bz on Bx during the minimum of the solar cycles 22, 23,24, and 25.

Moving on to figure 1(c), where we focused on the minimum of solar cycle 24, we observed an intriguing reversal in the solar magnetic field's polarity to negative. This unexpected shift in polarity during this period added complexity to the relationship between IMF Bz and Bx. The parabolic equation $Bz = (0.1552) + 0.0095(Bx) - 0.0082(Bx)^2$ characterizes the relationship between IMF Bz and Bx during the minimum of solar cycle 24 (2008–2010). The negative coefficient of the quadratic term (-0.0082) indicates a concave shape, similar to that observed during the minimum of solar cycle 22.

This implies a decreasing trend in IMF Bz as Bx increases, despite the opposite polarity of the solar magnetic field. The relatively high correlation coefficient ($R = 0.665$) between IMF Bz and Bx during the minimum of solar cycle 24 indicates a moderate relationship between these variables, although weaker compared to solar cycle 22. Finally, in Figure 1(d), we examined the minimum of solar cycle 25, which occurred between 2019 and 2021. Similar to solar cycle 24, the solar magnetic field maintained a negative polarity during this period. The parabolic equation $Bz = (0.2387) + 0.0147(Bx) -$

$0.0124(Bx)^2$ describes the relationship between IMF Bz and Bx during this minimum. The negative coefficient of the quadratic term (-0.0124) indicates a concave shape, consistent with the trends observed in solar cycles 22 and 24. The calculated second derivative of the equation (Bz'') being -0.0248 further confirms the downward trend or negative curvature in the relationship between IMF Bz and Bx during the minimum of solar

cycle 25. The relatively high correlation coefficient ($R = 0.704$) suggests a moderate relationship between IMF Bz and Bx during this period. The study provides further insights into the reversal of solar magnetic polarity during the minimum of solar cycle 24 and highlights the influence of solar magnetic field characteristics on the dynamics between IMF Bz and Bx during the minimum of solar cycle 25.

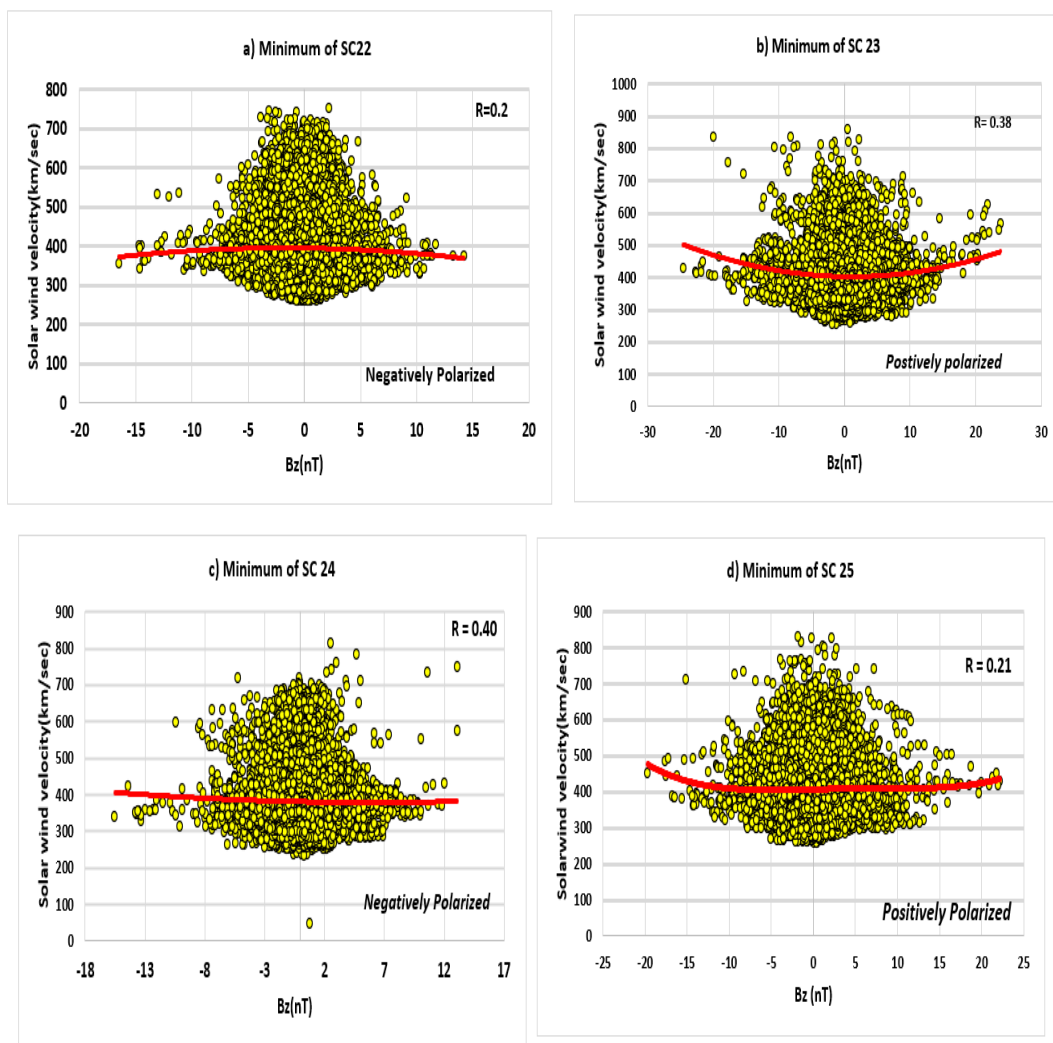


Figure 2. The dependence of IMF Bz on solar wind velocity during the minimum of the solar cycles 22, 23, 24, and 25, respectively.

The distribution of data points may not appear suitable for curve fitting in some cases. However, the use of a polynomial equation allows us to capture the underlying trend and relationship between the magnetic field components (Bx and

Bz) during the minimum activity phases. While the equation neglects the physical dimensions of the magnetic field, it provides a mathematical representation of the relationship between Bx and Bz, allowing us to quantify and analyze their

interplay. The coefficients in the polynomial equation help characterize the shape and curvature of the relationship, providing insights into the complex dynamics between these magnetic field components. It is important to note that the polynomial equation serves as a descriptive tool for the observed relationship, and further research is needed to investigate the underlying physical mechanisms and their dimensional implications.

In Figure 2, we examined the influence of IMF Bz on the solar wind velocity (V_{sw}) during the minimum activity levels of solar cycles 22, 23, 24, and 25. The curves 2 (a), (b), (c), and (d) correspond to the minima of solar cycles 22, 23, 24, and 25, respectively. Notably, we observed a distinct pattern of increasing solar wind velocity values as we progressed from cycle 22 to cycle 25. During the minimum of solar cycle 22, the solar wind velocity reached its lowest value of 275 km/s, while during the minimum of solar cycle 25, it peaked at 825 km/s. This progressive increase in solar wind velocity suggests a complex interplay between IMF Bz and the dynamics of the solar wind, possibly influenced by factors such as solar wind turbulence, variations, and the interaction between high-speed plasma flows and the interplanetary magnetic field. The observed dependency of IMF Bz on V_{sw} , as depicted in figure 2, can be attributed to several factors. One possible explanation is the presence of solar wind turbulence. Turbulent fluctuations in the solar wind can lead to variations in the interplanetary magnetic field, including IMF Bz. These fluctuations can arise from the complex interactions between the solar wind and the interplanetary medium, such as shock waves, plasma instabilities, and magnetic reconnection events.

The turbulent nature of the solar wind can introduce irregularities and fluctuations in IMF Bz, which, in turn, can affect the solar wind velocity. The solar

wind is not a uniform flow but rather exhibits spatial and temporal variations. These variations can result from changes in the source regions on the Sun, such as coronal holes, active regions, and eruptive events like solar flares and coronal mass ejections. Different solar wind conditions, characterized by variations in density, temperature, and magnetic field strength, can influence the behavior of IMF Bz and impact solar wind velocity. Furthermore, the interaction between high-speed plasma flows and the ambient interplanetary magnetic field can also play a role. When high-speed plasma streams encounter the interplanetary magnetic field, they can exert pressure and alter the configuration and strength of the magnetic field. This interaction can modify the behavior of IMF Bz, leading to changes in solar wind velocity.

The relatively low correlation values ($R=0.2$, $R=0.38$, $R=0.4$, $R=0.21$) between IMF Bz and solar wind velocity (V_{sw}) for Solar cycles 22, 23, 24, and 25 indicate that the relationship between these variables is not highly linear as shown in figure 2. However, it is important to note that solar cycles 22 and 24 exhibit a negative polarity of IMF Bz, while cycles 23 and 25 are positively polarized. This suggests that the polarity of the solar magnetic field plays a role in the observed dependency of IMF Bz on V_{sw} during periods of minimum solar activity. The observed dependency can be attributed to various factors, including solar wind turbulence, variations in solar wind conditions, and the interaction between high-speed plasma flows and the interplanetary magnetic field. These factors introduce complexities and nonlinearity into the relationship, leading to the parabolic trends observed in the correlation graphs. The nonlinear nature of these relationships indicates that multiple factors and mechanisms are at play, influencing the dynamics between solar magnetic polarity, interplanetary

magnetic field components (B_z and B_x), and solar wind velocity.

By studying the dependency of IMF B_z on V_{sw} during minimum solar activity periods, this research contributes to our understanding of the dynamics of space weather. It highlights the intricate interactions and dependencies between the solar magnetic field, interplanetary magnetic fields, and solar wind dynamics. These findings have implications for forecasting and predicting solar-terrestrial interactions, which are crucial for space weather forecasting and mitigating the potential impacts of space weather events on Earth and space-based systems. It is important to acknowledge that further research is needed to delve deeper into the underlying mechanisms and causal relationships between IMF B_z , solar wind velocity, and other influencing factors. Additionally, expanding the scope of the study to include different solar activity phases and these findings contribute to our understanding of the complex interactions within the heliosphere and provide valuable information for space weather predictions and forecasting. Further investigations are warranted to explore the underlying physical mechanisms and their implications for space weather phenomena and their potential impact on Earth and other celestial bodies in our solar system.

4 Conclusion

The present investigations have provided valuable insights into the relationship between interplanetary magnetic field (IMF) B_z , IMF B_x , solar wind velocity (V_{sw}), and the polarity of the Sun's magnetic field during periods of minimal solar activity. The following key conclusions can be drawn:

➤ Statistical studies of IMF B_z during four solar activity minima revealed distinct patterns. The opposite polarity of the Sun's magnetic field was observed between the years 1986-1988 and 2009-

2011, during weakly disturbed solar wind conditions.

➤ The analysis demonstrated that IMF B_z is dependent on IMFB x and solar wind velocity during the minimum activity of solar cycles 22, 23, 24, and 25. These dependencies suggest a complex interplay between the interplanetary magnetic field components and solar wind properties.

➤ The relationship between IMF B_z and solar wind velocity is influenced by the polarity of the Sun's magnetic field. Different behaviors were observed for positive and negative polarities, indicating a strong polarity-dependent effect.

➤ The formation of IMF B_z appears to be a homogeneous process that statistically depends on the condition of the solar wind. Factors such as solar wind turbulence, variations in solar wind conditions, and the interaction between high-speed plasma flows and the interplanetary magnetic field contribute to the observed dependencies.

➤ The findings support the concept of odd-even solar cycles. The opposing polarities of the solar magnetic field were observed during solar cycles 22 and 24 (even cycles), while positive polarities were observed during solar cycles 23 and 25 (odd cycles). This qualitative support strengthens the understanding of the odd-even concept.

Overall, this study enhances our understanding of the dynamics of space weather and the intricate relationships between solar magnetic polarity, interplanetary magnetic field components, and solar wind velocity during periods of minimum solar activity. The findings have important implications for forecasting and predicting solar-terrestrial interactions.

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