Origin of Solar Rotational Periodicity and Harmonics Identified in the Interplanetary Magnetic Field B_z Component Near the Earth During Solar Cycles 23 and 24

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Abstract Periodic variations in solar-wind and geomagnetic parameters have long been recognized. In this work, we examine the periodic properties in the interplanetary magnetic field (IMF) near the Earth using satellite observations from 1996 to 2017. We pay particular attention to short-term periodicities (solar rotational period and its harmonics) of IMF B_z by distinguishing between the geocentric solar ecliptic (GSE) and the geocentric solar magnetospheric (GSM) coordinates. We find that, for nearly all of the years in Solar Cycles 23 and 24, IMF B_z exhibits periodic changes with a period of the solar rotation or its harmonics or both. We emphasize that these changes are far more pronounced in the GSM coordinates than in the GSE coordinates and during the northern hemisphere spring and fall seasons than the other two seasons. We attribute this result to an exquisite harmony between the Russell–McPherron effect and a well-defined IMF polarity that shows either a two- or four-sector structure for a long period of time.

Keywords Interplanetary magnetic fields · Solar rotational periodicity · Solar wind

1. Introduction

The interplanetary magnetic field (IMF) originates from the Sun and extends continuously into interplanetary space. The IMF is the critical factor that determines major space disturbances around the Earth, such as magnetic storms and substorms. Coronal mass ejections (CMEs) from the Sun can carry a magnetic structure that has a large southward component, which can cause a geomagnetic storm through magnetic reconnection with the Earth's magnetic field (*e.g.*, Gonzalez *et al.*, 1994; Gopalswamy, Yashiro, and Akiyama, 2007). Even when there is no major CME occurrence, a southward component of the IMF can be supplied in other ways, such as a small-scale magnetic flux rope and Alfvénic fluctuations

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of the IMF within the solar wind, which can still be geo-effective (Zhang, Moldwin, and Cartwright, 2013; Choi *et al.*, 2017).

The detailed features of IMF near the Earth should be determined by arrival of the magnetic fields from the solar corona (known as the source surface field) as well as by local variations within the solar wind. It is clearly an important question to what extent the source surface field directly determines the IMF structure near the Earth. The answer should be complicated by various factors such as source surface field structure and its escape physics, transient solar activities and their propagation, and solar cycle and phase dependence, *etc.* To address this question, there have been many efforts to develop solar-wind models, some of which produce IMF in the heliosphere using the solar photospheric magnetic field observations. They include the tomographic model based on interplanetary scintillation observations developed at the University of California, San Diego (the UCSD model) (Jackson *et al.*, 2012, 2015, 2016), the Wang–Sheeley–Arge (WSA)–ENLIL model based on magnetohydrodynamics (Wang and Sheeley, 1990; Pizzo *et al.*, 2011), and a multiple flux-tube solar-wind model (Pinto and Rouillard, 2017). Despite these on-going efforts, it is still difficult to make a quantitatively precise assessment of the influence of the solar magnetic field on IMF. Nevertheless, some of the model results provide useful information. For example, in Jackson *et al.* (2015, 2016), the UCSD model combined with the current sheet source surface (CSSS) model (Zhao and Hoeksema, 1995) indicates that a small fraction of the normal component (B_n) flux in the North–South heliographic coordinates regularly escape from the low corona closed field regions. It is a good demonstration on how the solar field directly contributes to IMF B_z . Clearly our understanding of the relation between the solar magnetic field and IMF is still limited and much work remains to be done to improve it.

The main topic that we aim to study in this paper is periodic nature of IMF. In fact, it is well-known that the solar-wind and IMF parameters exhibit various periodicities. In particular, the periodicities of solar rotation and its harmonics, *i.e.*, ≈ 27 , ≈ 13.5 , ≈ 9 and ≈ 6.7 days, have been identified in the solar-wind speed (*e.g.*, Prigancová, 1992; Mursula and Zieger, 1996; Neugebauer *et al.*, 2000; Katsavrias, Preka-Papadema, and Moussas, 2012; Singh, Gautam, and Badruddin, 2012; Singh and Badruddin, 2015), solar-wind density (*e.g.*, Prabhakaran Nayer *et al.*, 2002), IMF total B (*e.g.*, Prabhakaran Nayer *et al.*, 2002; Singh, Gautam, and Badruddin, 2012; Singh and Badruddin, 2015), IMF B_x and B_y (*e.g.*, Rosenberg and Coleman, 1969; Wilcox and Gonzalez, 1971; Gonzalez and Gonzalez, 1987; Prigancová, 1992; Neugebauer *et al.*, 2000; Echer and Svalgaard, 2004; Katsavrias, Preka-Papadema, and Moussas, 2012), and IMF B_z (*e.g.*, Mursula and Zieger, 1996; Katsavrias, Preka-Papadema, and Moussas, 2012; Chowdhury *et al.*, 2014; Singh and Badruddin, 2015). In addition, some authors have reported similar periodicities in the geomagnetic field and its indices, such as the H value (*e.g.*, Poblet and Azpilicueta, 2018), Dst (*e.g.*, Katsavrias, Preka-Papadema, and Moussas, 2012; Singh and Badruddin, 2015), AE (*e.g.*, Katsavrias, Preka-Papadema, and Moussas, 2012; Singh and Badruddin, 2015), Ap (*e.g.*, Schreiber, 1998; Chowdhury *et al.*, 2014; Singh and Badruddin, 2017), and in cosmic-ray intensity (*e.g.*, Singh, Gautam, and Badruddin, 2012; Singh and Badruddin, 2017).

In the present work, we focus on IMF B_z and aim to determine its short-term (solar rotational and its harmonic) periodicities. Some previous work reported short-term periodicities of IMF B_z , a summary of which is given in Table 1. For example, Mursula and Zieger (1996) and Tschla, Gerontidou, and Mavronmichalaki (2019) used IMF B_z in GSM and found a dominant power at a ≈ 27 -day period and a weaker second harmonics. Chowdhury *et al.* (2014) and Gavryuseva (2018) examined IMF B_z in GSE and found the periodicity close to

Table 1 A summary of previous studies on periodic behavior of IMF B_z .

Study	Coord. of IMF B_z	Interval	Method	Period [day]
Mursula and Zieger (1996)	GSM	1964 – 1994	Welch averaged periodogram	27
Tsichla, Gerontidou, and Mavronmichalaki (2019)	GSM	1995 – 2018	Lomb–Scargle analysis	14.3, 28.5
			Wavelet transform	13.9, 27.8
Chowdhury <i>et al.</i> (2014)	GSE	2009 – 2013 Aug.	Lomb–Scargle periodogram	20, 26, 29, 30, 32, 34
			Wavelet transform	16 – 50
Gavryuseva (2018)	GSE	2003	Autocorrelation	29
Prabhakaran Nayer <i>et al.</i> (2002)	No information	1964 – 2000	Wavelet transform	240
Katsavrias, Preka-Papadema, and Moussas (2012)	No information	1966 – 2010	Lomb–Scargle periodogram	28, 30
			Wavelet transform	9 – 22 (13.9) ^a , 22 – 30 (27.8) ^a
Singh and Badruddin (2015)	No information	1995 – 1996, 2008 – 2009	Wavelet transform	1.9, 3.3, 4.2, 8.8, 9.5, –13.4, 13.8, 27.5, 28.3

^aThe values in parentheses refer to peak values within the indicated period ranges.

a solar rotational period and ≈ 29 and ≈ 30 days. Some papers report the short-term periodicities of IMF B_z without providing information on the coordinate system: Prabhakaran Nayer *et al.* (2002) found periodicities of 14 and 27 days, Katsavrias, Preka-Papadema, and Moussas (2012) reported 29–30-day periodicities, and Singh and Badruddin (2015) identified the solar rotation period and its harmonics.

Although the periodicities of IMF B_z have been reported in previous papers, we emphasize that our work here is distinguished from them in the following aspects. First, our work focuses on the comparison of IMF B_z between two distinguishing coordinates: the Geocentric Solar Magnetospheric (GSM) and Geocentric Solar Ecliptic (GSE) coordinates. We demonstrate that the short-term periodicities of IMF B_z should be addressed by distinguishing two coordinates and the results are quite different due to a reasonable cause that we demonstrate in Section 3. The previous works identified the periodicities based on the IMF B_z data either in one of the two coordinates or without providing specific information on the employed coordinates. Second, we pay attention to the IMF polarity or sector structure to address the origin of the periodicities found in the IMF B_z , which the previous works have not recognized. Lastly, our work is based on the IMF B_z data over the last two solar cycles.

Theoretically we expect that the solar source surface field should be critical in determining the nature of periodic behavior of IMF components. First, the source surface field at the solar corona is characterized by a distribution of the well-known sector structure, either toward or away from the Sun. We expect that, as this sector structure extends out into the heliosphere, it should determine to a large extent the local IMF polarity near the Earth. This local IMF polarity can be defined mainly by the signs of the IMF B_x and B_y (see Section 2). Therefore, it is reasonable to expect theoretically that the local IMF B_x and B_y polarity should reflect a distribution of the coronal source surface field polarity and accordingly IMF

B_x and B_y should exhibit the solar rotational periodicity and its harmonics (see Sections 3 and 4 for verification of this expectation). This periodicity in the local IMF B_x and B_y should be seen in both GSE and GSM. Next, we also expect that the coronal source surface field structure can affect local IMF B_z periodicity. To deduce the way it works, we pay attention to the well-known Russell–McPherron effect (Russell and McPherron, 1973) that when IMF is away from the Sun, there is the maximum possibility of southward IMF B_z in GSM around fall equinox, and when IMF is toward the Sun, such maximum occurs around spring equinox. Accordingly, the specific sector polarity of the coronal magnetic field should affect the behavior of IMF B_z in GSM in a season-dependent way, which is not present in IMF B_z in GSE. This will further influence any periodic behavior of IMF B_z in GSM, which may be absent or different in GSE. This is in fact the main point that we want to address in the present paper (Sections 3 and 4).

This paper is organized as follows. In Section 2, we explain the data and methods employed for the present analysis. In Section 3, we show the analysis results. In Section 4, we discuss a few issues related to the results. Lastly, we give the conclusions of this study in Section 5.

2. Data and Methods

We used the Operating Missions as Nodes on the Internet (OMNI) data base of NASA's Goddard Space Flight Center of the solar-wind and IMF parameters available at <http://omniweb.gsfc.nasa.gov/> over 22 years from 1996 to 2017, which covers Solar Cycles 23 and 24. For the IMF B_z component, we used the data in both GSE and GSM coordinates and compared the results.

The wavelet transform is a powerful tool of signal analysis in the way that signal power is expressed in a scalogram, which is defined by frequency or period *versus* time (Torrence and Compo, 1998). In contrast to a standard Fourier transform, a wavelet transform decomposes the signals using wavelets rather than a combination of sine and cosine functions. Furthermore, the wavelet transform does not lose the time information and gives a better signal representation by using a multiresolution analysis (Walnut, 2001) whereas the short-time Fourier transform has issues with the frequency time resolutions, which are time and frequency localized (*e.g.*, Sifuzzaman, Islam, and Ali, 2009). Prabhakaran Nayer *et al.* (2002), Katsavrias, Preka-Papadema, and Moussas (2012), Chowdhury *et al.* (2014), and Singh and Badruddin (2015) employed a wavelet technique to examine periodicities of IMF B_z .

In this study, we have employed the continuous wavelet transform technique with the Morlet wavelet function (order = 10) as the mother function. We have also produced the global power spectrum, which is the time-averaged wavelet spectrum over a certain narrow frequency band (Torrence and Compo, 1998). To complement the analysis, we have also used a standard Fourier transform.

The analysis we perform in this work relies on the local IMF polarity, namely, whether the IMF points toward or away from the Sun at the spacecraft measurement points. The variation in the IMF polarity is mainly due to a large-scale sector structure (often exhibiting two-sector or four-sector) and can be partly due to local fluctuations within the solar wind on a shorter time scale. For the purpose of the present work, we define the IMF polarity by following the idea of Bruno and Bavassano (1997) and Crooker *et al.* (1997). Specifically, we determine the IMF polarity by calculating the azimuthal angle that the daily averaged IMF B_x and B_y in GSE coordinates make with the theoretical Parker's spiral angle on the ecliptic plane, which we take to be 45° for the sake of simplicity. The IMF polarity is defined to be a toward

Figure 1 Power spectra obtained using the continuous wavelet transform for the solar-wind flow speed, IMF $|B|$, B_x , B_y , B_z in GSE coordinates and B_z in GSM coordinates from 1996 to 2017. The panels on the right side of each of the power spectra show the global power spectra in an arbitrary unit, which is the time-averaged wavelet spectra. The *black lines* refer to the cone of influence, below which edge effects become important.

or away from the sector according to whether the IMF azimuthal angle lies within or outside of the range of $\pm 90^\circ$. We have compared the determined polarity results with the sector list by Svalgaard available at <https://leif.org/research/> (Svalgaard, 1972, 1975a, 1975b). We found that two determination agrees with one another to a large extent ($\approx 87\%$ excluding the class of mixed sectors defined in the Svalgaard list but not in our work), although a complete agreement may not be expected due to the different methods of defining the sector boundaries used by Svalgaard. In Section 3, we will see that our definition of the IMF polarity is sufficiently adequate to address the main point of the present work.

3. Results

3.1. Overview of the Periodic Properties of the Solar Wind Variables During Solar Cycles 23 and 24

As we described in Section 2, we have applied the continuous wavelet transform with the Morlet wavelet function (order = 10) to the solar-wind speed and IMF data for an interval of 22 years corresponding to Solar Cycles 23 and 24. The results are shown in Figure 1. In each panel of the scalograms, the colors denote the wavelet power spectrum in a logarithm scale.

Figure 2 (a) IMF sector. (b), (c), (d) Wavelet power spectra and global power spectra in an arbitrary unit for IMF B_y , B_z (GSE) and B_z (GSM), respectively, during 2003.

The black bold curved lines over the scalograms are the cone of influence, below which edge effects become important at each frequency. Shown on the right sides of each scalogram is the global power spectrum, which is the time-averaged wavelet spectrum. The global power spectrum helps to identify some of the major periods that exist in the scalograms, although it contains no temporal information.

In the present work, we focus on identifying the solar rotational period (≈ 27 days) and its harmonics (≈ 13.5 , ≈ 9 days). Some of them are clearly identified as marked by horizontal arrows, indicating the first harmonic, ≈ 27 -day (black), and second harmonic, ≈ 13.5 -day (blue) in the global power spectrum panels in Figure 1. They are easily identified for the solar-wind speed, IMF B_x , B_y , and B_z in GSM. They may be discernible but less obvious for the IMF $|B|$ and even more difficult to identify for IMF B_z in GSE coordinates. In addition, even a ≈ 9 -day period (the third harmonic) can be identified for the solar-wind speed most obviously from ≈ 2004 to ≈ 2009 , and the IMF B_x and B_y from ≈ 2003 to ≈ 2006 and from ≈ 2013 to ≈ 2017 .

Although not shown here, we point out that, for IMF B_y , there is no major difference in the wavelet results between the GSM and GSE coordinates. In contrast, we stress that for IMF B_z the wavelet results are quite different between the two coordinates, such that the solar rotational and its harmonic periodicities seen in GSM are hardly identified in GSE. To identify the origin of this finding, in the following section we undertake a close examination on IMF B_z for each year during Solar Cycles 23 and 24.

3.2. Solar Rotational Periodicity and Its Harmonics in IMF B_z Found in 2003 and 2007

In this section, we demonstrate the periodic behavior of IMF B_z for two selected years, 2003 and 2007. In particular, we associate the periodicity of IMF B_z with the IMF polarity (or sector) structure at 1 AU.

Figure 2 shows the IMF sector structure and the power spectra of a continuous wavelet transform for IMF B_y in GSE and B_z in both GSE and GSM coordinates for 2003. In Figure 2a, we indicate the polarity of IMF sector by the two signs, 'X' and '.', representing the toward and away-sectors, respectively. Note that the vertical axis refers to the date of each month indicated on the horizontal axis. It is seen that the IMF polarity changes quasi-periodically with a period of less than a month, ≈ 27 days, corresponding to a solar rotation

Figure 3 Seven-day-averaged IMF B_z observed at 1 AU with the polarity of the IMF sector indicated at the top of each panel. The upper two panels are for the first half of the period of 2003 and the lower two panels are the second half of 2003.

period. It is clearly one of the better examples of the two-sector structure of the IMF. This is well revealed in the wavelet result for IMF B_y , where the highest power spectrum occurs at ≈ 27 days throughout the year 2003. A similar solar rotational periodicity is discernable for IMF B_z in GSE throughout the year 2003. However, note that the period somewhat increases in time. In contrast, IMF B_z in GSM exhibits a quite different periodic behavior than the solar rotational periodicity, which is pronounced mainly during the spring and fall seasons. The wavelet power of IMF B_z in GSM is much weaker during the other seasons, particularly near summer. This seasonal dependence is absent in GSE. Additionally, note that the power of the solar rotational periodicity during the spring and fall is more significant in GSM than in GSE. The global spectra indicate that the power of this periodicity in GSM is overwhelmingly peaked than in other periods, whereas in GSE there are multiple peaks comparable to the solar rotational periodicity. Therefore, there is a clear dependence on the coordinate system in the periodic behavior of IMF B_z . Most importantly, an obvious seasonal dependence occurs in GSM only, not in GSE.

To demonstrate the seasonal dependence found in Figure 2, we take a close examination on the IMF B_z data in 2003. In Figure 3, we display the IMF B_z data in GSE (blue lines) and GSM (red lines), along with the IMF sector polarity as indicated on the top of each panel by the 'X' and '.' signs, corresponding to the toward and away sectors, respectively, the same as shown in Figure 2. Here, to help visual clarification, we use a 7-day sliding averaged IMF B_z . We have identified two intervals surrounding each equinox as indicated by intervals A and B.

Figure 3 indicates that the IMF B_z in GSE (blue) fluctuates within $\pm$ a few nT. It can clearly be seen that during interval A in Figure 3 (spring in the northern hemisphere) the IMF B_z in GSM (red) is systematically shifted southward (northward) relative to the IMF B_z in GSE in association with the toward (away) sector of the IMF. A similar North–South shift, but in the opposite sense, is clearly identified for interval B (fall in the northern hemisphere). This North–South shift in association with the appropriate IMF polarity during the spring and fall seasons is well-known as the Russell–McPherron effect (Russell and McPherron,

Figure 4 (a) IMF sector. (b), (c), (d) Wavelet power spectra and global power spectra in an arbitrary unit for IMF B_y , B_z (GSE) and B_z (GSM), respectively, during 2007.

1973). In this paper, we refer the spring and fall seasons to those in the northern hemisphere. Since the IMF polarity is mainly of a well-defined two-sector and changes quasi-periodically throughout 2003, this causes the alternating North–South shift of IMF B_z in GSM with a period of ≈ 27 days during the spring and fall seasons. This is therefore the ultimate reason for the solar rotational periodicity pronounced mainly during the spring and fall seasons in the wavelet result in Figure 2.

Figure 4 shows another case in 2007 where the IMF polarity consists of a four-sector from January to early August, followed mainly by a two-sector structure for the remaining period. The four-sector IMF structure is well reflected in the IMF B_y wavelet result, indicating a clear periodicity at ≈ 13.5 days from January to early August. During this four-sector structure in the IMF, IMF B_z in GSM reveals the same periodicity, which is the second harmonic of the solar rotational periodicity. Note that this is heavily localized in the spring season due to the Russell–McPherron effect. Since August, the two-sector structure begins to dominate, which is well reflected in the IMF B_y wavelet result. Associated with this, the ≈ 27 -day periodicity of IMF B_z in GSM is far pronounced in the fall season again due to the Russell–McPherron effect. This seasonal dependence is absent in the IMF B_z in GSE, although it also shows a second harmonic periodicity in the spring, the power of which is, however, much weaker than that of IMF B_z in GSM.

Like in Figure 3, we take a close examination of IMF B_z for 2007 in Figure 5 in the same format as in Figure 3. The two intervals C and D marked in Figure 5 approximately represent the spring and fall seasons, respectively. From the 7-day-averaged B_z , it can clearly be seen that in the two intervals there is a systematic southward and northward shift of IMF B_z in GSM relative to IMF B_z in GSE, depending on the sector polarity of IMF due to the Russell–McPherron effect. Note that this North–South shift in IMF B_z in GSM occurs at a rate roughly two times higher in the spring due to the four-sector of the IMF than it does in the fall associated with mainly a two-sector IMF structure. This explains the main second harmonic periodicity in the spring and the primarily solar rotational periodicity in the fall seen in the wavelet result of IMF B_z in GSM in Figure 4. Note that IMF B_z in GSE itself also fluctuates to a weaker extent during the two intervals, but the Russell–McPherron effect amplifies the fluctuations and causes far more obvious sinusoidal oscillations in GSM. Additionally, in the other seasons IMF B_z is nearly equivalent for the two coordinates.

Figure 5 IMF B_z observed at 1 AU for 2007 shown in the same format as Figure 3.

3.3. Results for Other Years in Solar Cycles 23 and 24

To see if the solar rotational periodicity and its harmonics of IMF B_z in GSM in 2003 and 2007 remain true for other years, we have performed the same wavelet analysis on the periodicity for all years between 1996 and 2017. In particular, we paid attention to the seasonal dependence caused by the Russell–McPherron effect demonstrated for 2003 and 2007.

In Figures 6, 7 and 8, we present the wavelet power spectra of IMF B_y in GSE, and IMF B_z in two coordinates, GSE and GSM, with their global power spectra for 1996 to 2017. Compared to IMF B_z in GSE, it is the case for most of the years that IMF B_z in GSM indicates the solar rotational periodicity, or its second harmonics, or both, which is pronounced in the spring or fall, which is consistent with the corresponding periodicities in IMF B_y . This suggests that in Solar Cycles 23 and 24 a well-defined IMF sector structure, either a two- or four-sector most of the time, prevails and repeats quasi-periodically for a sufficiently long interval. As combined with the Russell–McPherron effect, it creates the solar rotational periodicity and its second harmonics in IMF B_z in GSM primarily in the spring and fall seasons.

On the other hand, in Figures 6, 7 and 8 we identify a few intervals that do not indicate a solar rotational periodicity and its harmonics in IMF B_z in GSM, even though IMF B_y indicates such periodicities. These exceptional times are denoted by black triangles in Figures 6, 7 and 8. In spring 1997, fall 2005, and spring 2006, IMF B_y indicates a ≈ 27 -day periodicity, but the same periodicity is not clearly identified in IMF B_z in GSM. Additionally, in spring 2012 shown in Figure 8, while IMF B_y exhibits a ≈ 13.5 -day periodicity, the same periodicity does not occur in IMF B_z in GSM. These all may appear as inconsistent with our explanation above based on the Russell–McPherron effect in association with the IMF sector conditions. However, we caution the reader by stressing that sometimes the periodicity in IMF B_y appearing in the wavelet results does not necessarily imply the periodic oscillation between two IMF polarities defined in Section 2. Sometimes IMF B_y can exhibit periodic changes even without changing its signs, while the Russell–McPherron effect depends largely on the sign of IMF B_y . We explain this in Figure 9 with an example.

Figure 6 Wavelet power spectrum and the global power spectra in an arbitrary unit for IMF B_y , B_z (GSE) and B_z (GSM) from 1996 to 2003.

Figure 9 shows the 7-day running averaged IMF B_y and B_z for January–June 2012. Panel (a) indicates that IMF B_y oscillates in half the solar rotation period, which explains the ≈ 13.5 day periodicity in the wavelet result of IMF B_y in Figure 8. However, note that while oscillating, IMF B_y , particularly from February to April, remains positive for much shorter times and is of a weaker magnitude (yellow highlight) than when it is negative. The green highlight interval refers to the time when a positive IMF B_y may be expected from the earlier waves but is actually absent. Due to this asymmetry in IMF B_y between positive and negative polarities, the Russell–McPherron effect results in less of a northward shift of IMF B_z in GSM compared to its southward shift. Consequently, in the resulting IMF B_z in GSM in panel (b), a 13.5-day periodic variation is much less obvious throughout the spring

Figure 7 Same as Figure 6 except for 2004 to 2011.

interval. This explains the absence of the 13.5-day periodicity in IMF B_z in GSM, while the same periodicity exists in IMF B_y in Figure 8. Although the data are not shown here, a similar explanation applies to the cases of spring 1997, fall 2005, and spring 2006, where the IMF B_y variation contains a ≈ 27 -day periodicity to some extent, but the IMF B_y polarity change is not quite symmetric between the positive and negative signs. This explains why there is no obvious periodicity in the wavelet result of IMF B_z in GSM, but it does not mean there is inconsistency with the Russell–McPherron effect.

Despite a few exceptional situations, the seasonal dependence of the periodicity in IMF B_z in GSM is an overall robust feature in Solar Cycles 23 and 24. To demonstrate this further in a simple way, we divide the 22 years of the IMF B_z data into four groups, roughly representing four seasons. Each season of every year includes 121 days (about four months),

Figure 8 Same as Figure 6 except for 2012 to 2017.

Figure 9 Seven-day-averaged IMF B_y (in GSE) and B_z (in GSE and GSM) observed at 1 AU in January to June 2012 with the polarity of IMF sector shown at the top of (a).

such that adjacent seasons overlap by $\approx$ one month. The starting dates of the four seasons are fixed to February 1, May 1, August 1 and November 1, respectively. From the starting date, all of the seasons have been defined for 121 days, which include solstices and equinoxes. For each of the four groups, we have performed FFT power spectrum analyses and averaged the resulting power spectra over 22 years for each season. Figure 10 shows the results obtained for IMF B_z in the GSE and GSM coordinates. They clearly indicate the notable differences between the two coordinates. The main difference is characterized by the feature that the solar rotational periodicity and its harmonics (up to third harmonics having a ≈ 9 days periodicity) are far more prominent in GSM, and much less obvious in GSE; Other

Figure 10 Power spectra obtained by applying FFT to IMF B_z with distinction among four seasons from 1996 to 2017.

than these peaks in GSM, the overall shapes (background trend) of the power spectra are similar between the two coordinates. More importantly, in GSM there is a clear dependence on seasons, where the periodicity is prominent in spring and fall. For the solar rotational periodicity, the peak power of spring and fall (red and blue) is larger by approximately two times than that of summer and winter (green and black, respectively), and a similar seasonal dependence is discernable even for the third harmonics. This major difference between the two coordinates is due to the Russell–McPherron effect as demonstrated in Section 3.2. Recall that the wavelet results in Figures 6, 7, and 8 indicate that this effect prevails throughout the entire two solar cycles. Therefore, the season-dependent peaks in the FFT results for IMF B_z in GSM in Figure 10 simply confirm the features revealed in the wavelet results in Figures 6, 7, and 8.

4. Discussion

Here, we discuss a few aspects related to the results in Section 3. First, although IMF B_z in GSM reveals much more significant periodic properties in the spring and fall under the condition of repetitive changes of well-defined IMF polarity, we discuss the extent to which IMF B_z in GSE also reveals a similar periodicity. Second, we discuss if there is any solar cycle dependence for the periodicity of IMF B_z in GSM. Lastly, we discuss the relation of the IMF polarity structure with the source surface field near the Sun for the intervals in 2003 and 2007.

4.1. Possible Periodicity in IMF B_z in GSE

While we have focused on the periodic behavior of IMF B_z in GSM in Section 3, there are some studies that examined the periodicity of IMF B_z in GSE (e.g., Chowdhury *et al.*, 2014; Gavryuseva, 2018). Chowdhury *et al.* (2014) used the Lomb–Scargle periodogram and wavelet transform technique to analyze solar-wind parameters and IMF B_z in GSE from 2009 to August 2013, and found various short-term periodicities, close to solar rotation periods of 20, 26, 29, 30, 32, 34 days (shown in Figure 2(a) in their paper) and 16 to 50 days (shown in Figure 2b in their paper). They did not suggest any explanation on the origin of the identified periodicities. In our work, Figures 7, 8 indicate somewhat similar periodicities during the same interval, such as a weak solar rotational periodicity in May to August 2009, a periodicity of slightly longer than 30 days in 2010, no rotational periodicities and overtones in summer 2012 (but without a clear peak at the solar rotational period), and a very

weak solar rotational periodicity around April 2013. Gavryuseva (2018) studied the variation in photospheric and interplanetary magnetic field data and found a 29-day periodicity in IMF B_z in GSE during 2003 using an autocorrelation analysis (shown in Figure 6 in their paper) and mentioned that perhaps B_z is mainly sensitive to the fast wind from the polar coronal holes. This is also discernible in our wavelet result (Figure 6), although the period is not constant but varies weakly throughout the year (it becomes longer toward the end of the year). Other than these intervals studied in Chowdhury *et al.* (2014) and Gavryuseva (2018), we can identify some other intervals from Figures 6, 7 and 8 in our study when a solar rotational periodicity and its harmonics of IMF B_z in GSE are discernible. They may include October–December 1998, the spring and fall in 2002, the spring in 2005 (weak solar rotational period), January–April in 2006 (weak solar rotational period), spring of 2007 (second harmonics), the spring and fall in 2008 (weak solar rotational period and second harmonics), the spring and fall 2014, 2015, February–October 2016, and April–July 2017, all of which have not been reported in the previous studies.

However, even if they are identified in GSE, the power of these waves is mostly very low compared to those of IMF B_z in GSM, the fact that is confirmed in the FFT results in Figure 10. In addition, the identified periodicities in IMF B_z in GSE are much less systematic than those found in GSM in the sense that some of them exhibit a period that varies in time and is rather different from 27 days, and most importantly there is no seasonal dependence that is identified in GSM.

4.2. Solar Cycle Dependence

In this work, we used the data from 1996 to 2017, which covers Solar Cycles 23 or 24. Previous works (*e.g.*, Gopalswamy *et al.*, 2015; Gopalswamy, Yashiro, and Akiyama, 2016; Janardhan *et al.*, 2018) report that Solar Cycle 24 is characterized by a smaller magnitude of the solar magnetic field and milder space weather in comparison with Solar Cycle 23. Janardhan *et al.* (2018) studied the solar magnetic field in a latitude range (as shown in their Figure 5) and found that the polar field strength in the north reached its minimum values much earlier than the south, showing the hemispheric phase shifts in the polar field reversal process in Cycle 24. They claimed that the magnetic field strength during the declining phase of Cycle 24 is much weaker than that in Cycle 23. If the solar magnetic field is weaker such that IMF B_y is accordingly of a smaller value, then it would mean a less strong Russell–McPherron effect, thus possibly leading to a weaker periodicity in IMF B_z in GSM. Indeed, our wavelet result in Figure 1f indicates that the power of the ≈ 27 -day period wave is overall lower during Solar Cycle 24 than during Cycle 23. Despite this difference, the solar rotational periodicity and its harmonics are found to occur in IMF B_z in GSM for most of the years in both Solar Cycles 23 and 24 with little difference in the occurrence rate, as shown in Figures 6, 7 and 8. In other words, the basic mechanism based on the Russell–McPherron effect in coordination with the appropriate IMF polarity changes works successfully to lead to season-dependent periodic behavior in IMF B_z in GSM, regardless of the solar cycle.

4.3. Comparison Between SSF and IMF

In Section 3 we emphasized the critical role of the local IMF polarity structure in determining the solar rotational periodicity and its harmonics of IMF B_z in GSM. We find that the IMF polarity near the Earth is mostly of a two- or four-sector structure for Solar Cycles 23 and 24, which is the critical factor that determines the periodicity in IMF B_z in GSM as combined with the Russell–McPherron effect. A naturally arising question is if the local

Figure 11 Coronal magnetic field map calculated by potential field source surface (PFSS) model from the Wilcox Solar Observatory (WSO) for selected intervals in 2003 and 2007. Negative and positive polarities are marked by *dark gray* and *light gray*, respectively. Thin contours refer to a constant magnetic field magnitude of $\pm 1, 2, 5, 10, 20 \mu\text{T}$. *Thick black lines* refer to the neutral current sheet. The *colored horizontal lines* refer to the coronal projection of the Earth location where the IMF is measured.

IMF polarity measured near the Earth originates directly from the Sun, which then would imply a direct association of the IMF B_z periodicity to the solar condition. To address this question, here we use the potential field source surface (PFSS) model, which is based on photosphere magnetic fields as input, available from Wilcox Solar Observatory (WSO). Although there are issues related to the choice of the location of the source surface field as the model input data (e.g., Koskela, Virtanen, and Mursula, 2017), we have chosen the classic source surface distance of $2.5R_s$ as the height where the PFSS calculates the coronal source field (Hoeksema, Wilcox, and Scherrer, 1983). The results of the PFSS model magnetic field polarity at $2.5R_s$ are shown in Figure 11 for selected intervals in 2003 and 2007. The longitudinal angle corresponds to the time at which observations measured the magnetic field of the photosphere which is needed as input to the PFSS model. The angles from 360° to 0° in longitude are the time interval from the start to end of the corresponding Carrington Rotation (CR). The polarity of the source surface magnetic field is presented by two colors, dark and light gray, referring to negative and positive polarity, respectively, and the contours represent the magnetic field magnitude, such that the thick black line refers to 0 and the thin lines $\pm 1, 2, 5, 10$, and $20 \mu\text{T}$. The colored horizontal lines refer to coronal projection of the Earth for the intervals that include A and B in 2003 (Figure 3) and C and D in 2007 (Figure 5). They were determined by considering the effect of the propagation time from the

Sun to the Earth based on a constant solar-wind speed model and the heliographic latitude of the Earth following Koskela, Virtanen, and Mursula (2017).

Figure 11a shows the coronal source surface field from CR 1999 to CR 2002, including the interval from 1 February 2003 to 30 April 2003 (red lines) corresponding to interval A in Figure 3. Figure 11a indicates that the structure of the source surface field is well organized and characterized by well-defined two polarity sectors over a wide latitudinal range. It is consistent with the two-polarity sector structure of IMF near the Earth in Figure 2. In the modeled source surface field, the red line starts near $\approx 270^\circ$ in CR 1999 and ends near 210° in CR 2002. Along this red line, the polarity was initially negative in CR 1999, became positive across the neutral line (thick black line) and then alternated between negative and positive polarities through CR 2002. This is consistent with the observed IMF polarity change shown in Figure 3 where the IMF is of the toward sector at the beginning of interval A and alternates between away and toward at a solar rotation period. The situation is the same for interval B where the polarity change of the source surface field in Figure 11b is consistent with the alternating two-sector structure of IMF in Figure 5.

Similarly, Figures 11c and 11d show the PFSS results for intervals in 2007, which include intervals C and D in Figure 5. Figure 11c indicates that the green line crosses the neutral line (black bold line) four times from right to left through one Carrington rotation period. This four-sector structure is consistent with the IMF polarity variation at a period of ≈ 13.5 days in Figure 5. Note that from CR 2059 the neutral line for longitude $> 180^\circ$ is located below the equator. Consequently, the heliographic latitude of the Earth is continuously above the neutral line at the longitude between 180° and 360° , so that the blue horizontal line for interval D crosses the neutral line twice for one Carrington rotation period, which is reflected as a two-polarity structure of IMF and leads to its ≈ 27 -day periodicity.

These examples in 2003 and 2007 imply that the IMF polarity structure at 1 AU is determined largely by the longitudinal and latitudinal distributions of the source surface field polarity and the heliospheric current sheet latitude relative to the heliographic equator. The statistical results by Koskela, Virtanen, and Mursula (2017) indicate that the average polarity match between the coronal model field (predicted by PFSS) and IMF (measured in situ near the Earth) is well above 70%. Therefore, this leads us to expect that the periodic behavior of IMF B_z in GSM is largely determined by the structure of the coronal field polarity. A more precise determination of the extent to which this expectation holds is left as future work.

5. Conclusion

In this work, we examined the short-term periodicities (solar rotational period and its harmonics) in IMF B_z near the Earth using the observations from 1996 to 2017. We emphasized the use of two distinguishing coordinates, GSE and GSM coordinates. Based largely on the continuous wavelet transform analysis and a standard Fourier transform as a complement, we find that, for nearly all of the years in Solar Cycles 23 and 24, IMF B_z exhibits periodic changes with a period of solar rotation or its harmonics or both. We emphasize that these changes are far more pronounced in the GSM coordinates than in the GSE coordinates and that there is a robust seasonable dependence of the periodicities in GSM that are seen primarily during the northern hemisphere spring and fall seasons. We attribute this result to an exquisite harmony between the Russell–McPherron effect and a well-defined IMF sector structure that often maintains either two or four sectors for a sufficiently long period.

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