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Systematic investigation of mid-term periodicity of the solar full-disk magnetic fields

Nan-Bin Xiang

Yunnan Observatories, Chinese Academy of Sciences, Kunming 650011, China; *nanbin@ynao.ac.cn*
CAS Key Laboratory of Solar Activity, National Astronomical Observatories, Beijing 100101, China
Key Laboratory of Dark Matter and Space Astronomy, Purple Mountain Observatory, Nanjing 210008, China

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Abstract The Magnetic Plage Strength Index (MPSI) and the Mount Wilson Sunspot Index (MWSI), which have been measured at Mount Wilson Observatory (MWO) since the 1970s and which indicate weak and strong magnetic field activity on the solar full disk, respectively, are used to systematically investigate mid-term periodicities in the solar full-disk magnetic fields. Multitudinous mid-term periodicities are detected in MPSI and MWSI on timescales of 0.3 to 4.5 yr, and these periodicities are found to fluctuate around several typical periodicities within a small amplitude in different solar cycles or phases. The periodicity of 3.44 yr is found in MPSI, and the periodicities of 3.85 and 3.00 yr are detected in MWSI. Our analysis indicates that they reflect the true oscillating signals of solar magnetic field activity. The typical periodicities are 2.8, 2.3 and 1.8 yr in MPSI and MWSI, and possible mechanisms for these periodicities are discussed. A 1.3 yr periodicity is only detected in MPSI, and should be related to meridional flows on the solar surface. The typical annual periodicity of MPSI and MWSI is 1.07 yr, which is not derived from the annual variation of Earth's heliolatitude. Several periodicities shorter than 1 yr found in MPSI and MWSI are considered to be Rieger-type periodicities.

Key words: Sun: general — Sun: activity — Sun: magnetic fields

1 INTRODUCTION

In the study of solar physics, finding periodic signals in many types of solar activity and investigating periodicities of a time series are traditional and classical methods, since many solar physical processes have periodic or quasi-periodic signals, and the nature and physical significance of solar activity can be revealed through the analysis of periodicities in these signals (Akioka et al. 1987; Lean 1990; Li et al. 2012). For instance, early papers related to analyses of the periodicities in solar activity indicators reported that the dominant cycles are the 11-year Schwabe cycle and the 22-year magnetic cycle. Moreover, in addition to these significant cycles, many solar activity indicators show variations on all timescales, i.e., minutes to decades, and these variations are related to evolution of the solar magnetic field on the solar surface and may be linked to the solar dynamo (Knaack et al. 2005; Domingo et al. 2009; Vecchio et al. 2012; Ulrich & Tran 2013; Qu & Xie 2013; Xiang & Qu 2016).

So far, many papers have analyzed the periodicities and evolutionary characteristics of solar magnetic activity on different timescales, especially focused on the analysis of mid-term periodicities (several months to years). Krivova & Solanki (2002) found a 1.28 yr periodicity in the tracers of relatively freshly emerged flux (namely sunspots) on the solar surface, and this variation was observed to vary strongly with time. Ikhsanov & Ivanov (2004) analyzed the magnetic data observed by the Wilcox Solar Observatory (WSO) of Stanford University (1976−2004) and the National Solar Observatory (NSO/Kitt Peak) (1970−1984), and revealed a period of about 1.3 yr in the larger-scale solar magnetic field. Furthermore, this period of the larger-scale solar magnetic field was validated in later papers (Knaack et al. 2005; Obridko & Shelting 2007). Wang & Sheeley (2003) and Wang (2004) suggested that the nearly 1.3 yr periodicity in solar magnetic field activity should be derived from the stochastic interaction of local fields and meridional flows on the solar surface; Knaack et al. (2005) agreed with this interpretation, and they asserted that the large-scale magnetic surges toward the poles in both hemispheres at intermediate latitudes during the maxima of solar cycles caused this periodicity. On the other hand, Howe et al. (2000) and Komm et al. (2003, 2004) found that the solar rotation rate at the equator of the base of the convection zone has a 1.3 yr periodicity, and then Christensen-Dalsgaard (2007) reported that solar rotation in the narrow tachocline is alternately faster and slower, and the mean amplitude of the rotation rate variation increases towards the solar equator. At the same time, the reversing east-west flows near the detectable limit at the solar surface are shown to change direction every 1.3 yr (Wolff & Mayr 2004). In addition, magnetographic data measured at the Mount Wilson Observatory (MWO) were utilized to study the rotation velocity measurements. Javaraiah (2003) stated that the variation of solar surface rotation rate has a 1.3 yr periodicity as well. Hence, these studies indicated that the nearly 1.3 yr periodicity of the solar rotation rate at the equator of the base of the convection zone should propagate to the solar surface and interplanetary space (1 AU and higher) (Prabhakaran Nayar et al. 2002; Mursula & Vilppola 2004). Though no study demonstrates that the nearly 1.3 yr periodicity of solar magnetic field activity on the disk is directly related to the variation of internal rotation rate of the Sun, we still consider whether the nearly 1.3 yr periodicity should be an independent oscillation in each layer from tachocline (rotation rate) to solar surface (e.g., sunspot and large-scale magnetic field), or whether these oscillations should be derived from the internal rotation of the Sun.

Other significant mid-term oscillating periodicities of solar magnetic field activity on the disk were detected as well, such as 1.5, 1.8 and 3.6 yr (Knaack et al. 2005). The periodicities of $1-1.5$ yr are detected at the polar and high-latitude fields, while the mid- and low-latitude solar events have characteristic periodicities of 1.3 and 1.7 yr respectively (McDonald et al. 2005; Cadavid et al. 2005). Moreover, the wavelet technique was utilized by Mendoza et al. (2006) to investigate the mid-term periodicities in different types of solar magnetic flux (total, closed, open, and low and high latitude open fluxes). They found that all fluxes had a dominant fluctuation with a period of 1.7 yr, which always appeared during the declining phase of solar cycles, and the significant fluctuation of 1 yr was only present in the total and closed fluxes, while being less important in open flux. However, the 1.3 yr periodicity cannot be discriminated because of uncertainties associated with analysis using the wavelet technique.

Recently, Xiang et al. (2014) studied the periodicities of both strong and weak magnetic field activity on the disk. However, mid-term periodicities were ignored because of the mathematical method employed in that study. Feng et al. (2017) used the synchrosqueezing transform to decompose the periodic modes of weak and strong magnetic field activity, which are represented by the Magnetic Plage Strength Index (MPSI) and Mount Wilson Sunspot Index (MWSI), respectively. However, a continuous time series is needed when the synchrosqueezing transform is applied. The MPSI and MWSI utilized in Feng et al. (2017) have records in 11 084 d of the total 15 344 d from 1970 January 19 to 2012 January 22, and they are expressed as uneven time series. The missing records amount to 27.8%, which take up a relatively large percentage. In particular, the two indices have only several or ten more records in annual winter. The linear interpolation method employed in that paper to make them continuous is inappropriate since it will introduce a large amount of noise, which should lead to detection of artificial periodicities, though the synchrosqueezing transform is a good method to decompose the periodic modes of a continuous time series. Consequently, further investigations on this topic are significant and necessary. In this study, we use the Lomb-Scargle algorithm, which is particularly suitable for investigating periodic signals for uneven time series with a considerable percentage of missing records, to detect the mid-term periodicities and evolutionary characteristics of both strong and weak magnetic field activity on the solar full disk, and attempt to study the physical process and reason behind these mid-term oscillations.

2 INVESTIGATION OF MID-TERM PERIODICITIES IN THE SOLAR WEAK AND STRONG MAGNETIC FIELD

2.1 Data

Many papers (for more details see Howard et al. 1980, 1983; Chapman & Boyden 1986; Ulrich 1991; Ulrich et al. 1991; Parker et al. 1998; Li et al. 2014) and our recent studies (Xiang et al. 2014; Xiang & Kong 2015) indicated that the two indices, which come from the solar full-disk magnetic magnetogram measured at the MWO since the 1970s, can reflect the solar full-disk magnetic field activity. These authors advised that one is the MPSI, which represents the weak magnetic field activity (with plage/facular regions and outside of sunspots) on the solar full disk; and the other is the MWSI, which can signify strong magnetic field activity (in sunspots) on the disk. The two indices can be downloaded from MWO (*http://obs.astro.ucla.edu/intro.html#plots*). In this study, we apply the two indices (MPSI and MWSI) to investigate mid-term periodicities of the weak and strong magnetic field activity on the solar full disk, respectively.

Figure 1 shows the daily MPSI and MWSI measured at MWO from 1970 January 19 to 2013 January 31. Based on the 12-month running means of the monthly mean values of the two indices, the maxima times of MPSI (MWSI) in solar cycles $21-23$ are in 1981 March (1981 November), in 1991 April (1990 December) and in 2002 January (2001 November); the minima times of MPSI (MWSI) in so-

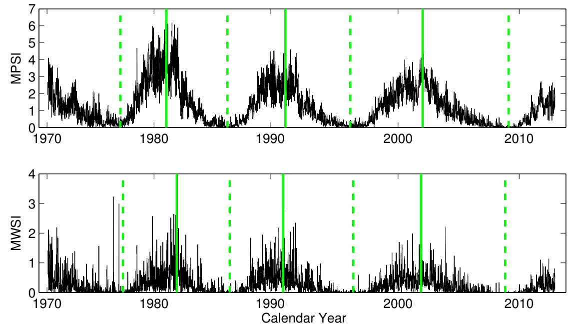

Fig. 1 Two indices: the daily MPSI (*top panel*) and the daily MWSI (*bottom panel*) measured at MWO from 1970 January 19 to 2013 January 31. The *dashed* (*solid*) *green lines* in the top and bottom panels indicate the minima (maxima) times of MPSI and MWSI in cycles 21−24, respectively (*color version is online*).

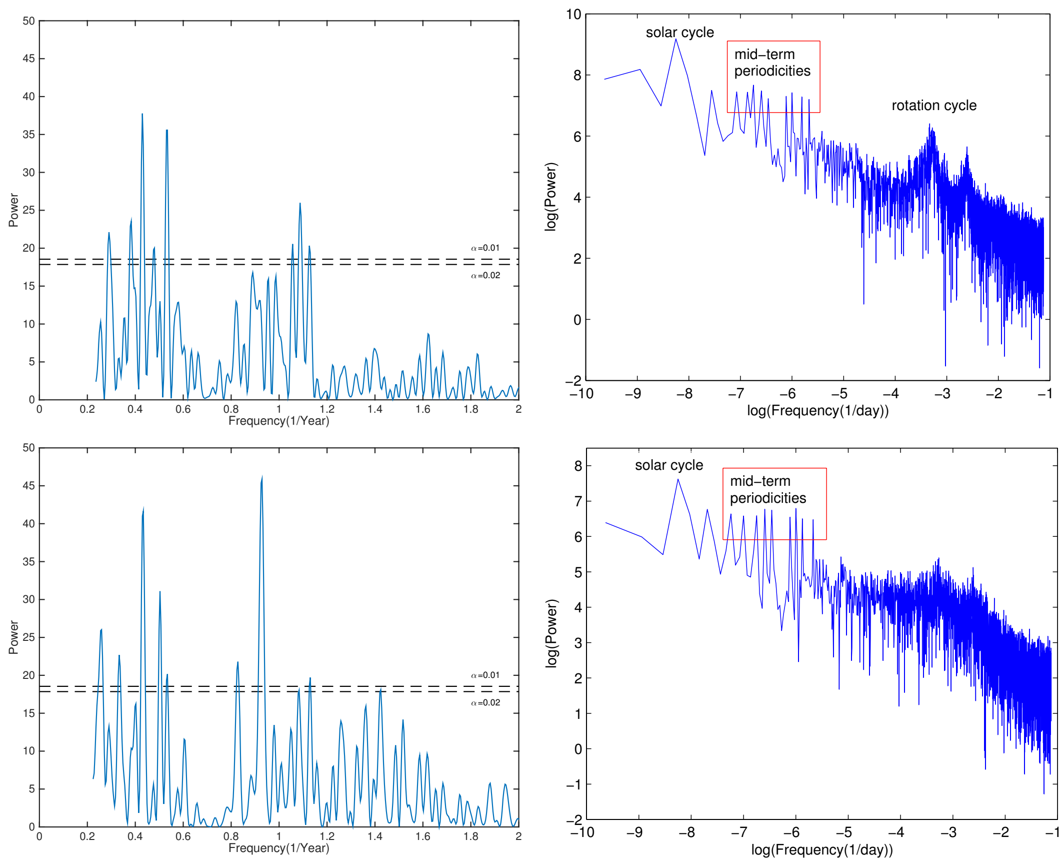

Fig. 2 *Left column*: LSPs of the daily MPSI (*top panel*) and MWSI (*bottom panel*) in cycles 20−24. The x-axis and y-axis in the two panels indicate the range of examined frequencies and the power corresponding to each frequency, respectively. The two *dashed horizontal lines* in each panel show the 0.01% and 0.02% significance level, respectively. *Right column*: The Fourier power spectra of daily MPSI (*top panel*) and MWSI (*bottom panel*) during the same time interval.

lar cycles 21−24 are in 1976 October (1976 December), in 1986 August (1986 September), in 1996 June (1996 August) and in 2008 December (2008 September). All the results are also shown in Figure 1, where the dashed (solid) green lines in the top and bottom panels indicate the minima (maxima) times of MPSI and MWSI in cycles 21−24. There, the minimum (maximum) times of MPSI and MWSI given in each cycle may have a small deviation compared with the actual minimum (maximum) times. However, the small deviation should not affect the investigation results in this study.

2.2 Mid-term Periodicities of MPSI and MWSI

In a variety of periodicity analysis methods, the Fourier transform is a traditional and classical tool which connects the time domain with the frequency domain. Because of the need to deal with different types of data, there are several different Fourier methods, such as Discrete Fourier Transform (DFT), Date-Compensated Discrete Fourier Transform (DCDFT), Lomb-Scargle algorithm, etc. For the two indices (MPSI and MWSI) of uneven time series, the Lomb-Scargle periodogram (LSP) is quite a robust tool for spectral analysis and statistical significance testing of periodic signals, since this method can alleviate the problem of missing data (Lomb 1976; Scargle 1982; Horne & Baliunas 1986; Qu & Xie 2013; Xu & Gao 2016; Li et al. 2017). Hence, we use LSP to detect the mid-term periodicities of MPSI and MWSI.

MPSI and MWSI have been measured at MWO since the 1970s, and the two time series contain the entire solar cycles 21−23, as well as the declining phase of cycle 20 and the ascending phase of cycle 24. In order to exactly investigate the mid-term periodicities of MPSI and MWSI as well as the relationship of a certain periodicity with the phase of solar cycle, firstly, the entire time series of MPSI and MWSI is taken into account to detect the mid-term periodicities. Then, we analyze the mid-term periodicities of MPSI and MWSI in each of the entire solar cycles 21−23 and in the ascending/declining phases of solar cycles 20−24.

2.2.1 *Mid-term periodicities of the MPSI and MWSI in cycles 20−24*

The LSPs of daily MPSI and MWSI from 1970 January 19 to 2013 January 31 are displayed in the left column of Figure 2. The range of examined frequencies is about 0.22−2 (1/Year), which corresponds to the range of examined periodicities of about 0.5−4.5 yr. At the same time, only those periodicities that are statistically significant at the 99% or 98% confidence level are taken into account. The mid-term periodicities of daily MPSI and MWSI displayed in Figure 2 are also given in Table 1. From these results, we can see that the two indices (MPSI and MWSI) have complex oscillations on timescales of 0.5 to 4.5 yr. In order to validate whether these mid-term periodicities of daily MPSI and MWSI detected by LSPs are real oscillations, we also use the method of fast Fourier transform to analyze the two time series again, and the Fourier power spectra of daily MPSI and MWSI are shown in the right column of Figure 2 in the top and bottom. There, the gaps in two time series are filled by the nearest neighbor resampling method suggested by de Waele & Brosersen (2000), since it is robust and provides an unbiased estimate of variance, while the more sophisticated interpolation methods, such as linear interpolation and cubic interpolation, may have divergence problems such that the variance is estimated erroneously. As the top right panel of Figure 2 demonstrates, there are some prominent peaks in the three regions of the Fourier power spectrum of daily MPSI, which should indicate the solar cycle, mid-term periodicities and rotational periods from left to right, respectively. Similarly, the Fourier power spectrum of daily MWSI also displays some prominent peaks on timescales of about 1 to 4 yr, which correspond to mid-term periodicities. Furthermore, we also compare these mid-term periodicities obtained by two methods, and find that the results from the two different methods appear quite similar. The small deviation of these periodicities detected by the two methods should be attributed to interpolation when we use the fast Fourier transform. Consequently, we can conclude that these oscillations of daily MPSI and MWSI at mid-term timescales are real signals, and the LSP method as well as the statistical significance test used in this study is suitable for investigating the mid-term periodicities of two time series. Alternatively, the method of autoregressive moving average selection for irregular data suggested by Broersen (2009) is also suitable for investigating the periodicities of the two indices.

2.2.2 *Mid-term periodicities of the daily MPSI and MWSI in each entire solar cycle 21−23*

Figure 3 displays the LSPs of the daily MPSI (left column) and MWSI (right column), in solar cycles 21, 22 and 23 from top to bottom panels, respectively. In order to investigate the mid-term periodicities of the two indices, the range of examined periodicities is about 0.5−3 yr. We also take into account the periodicities which are of statistical significance at the 99% and 98% confidence level. The mid-term periodicities of daily MPSI and MWSI depicted in Figure 3 are also given in Table 2.

As shown in Figure 3 and Table 2, the two indices (MPSI and MWSI) have complex oscillations at mid-term timescales, and the periodic oscillations of MPSI (MWSI) in solar cycles 21, 22, and 23 are different from each other. Furthermore, both MPSI and MWSI display more mid-term oscillating periodicities in solar cycle 23 than in the other two solar cycles. It seems that the solar magnetic field activity on the solar full disk during solar cycle 23 is more complex than that during solar cycles 21 and 22, though the smaller values of MPSI and MWSI in this cycle exhibited in Figure 1 indicate weaker magnetic field activity. That is to say, the complexity of solar magnetic activity on the disk should not be directly related to the magnetic field strength.

2.2.3 *Mid-term periodicities of the MPSI and MWSI in ascending and declining phases of cycles 20−24*

In order to further study the reasons causing the mid-term periodicities of the two indices, and investigate the relationship of a certain periodicity with phases of the solar

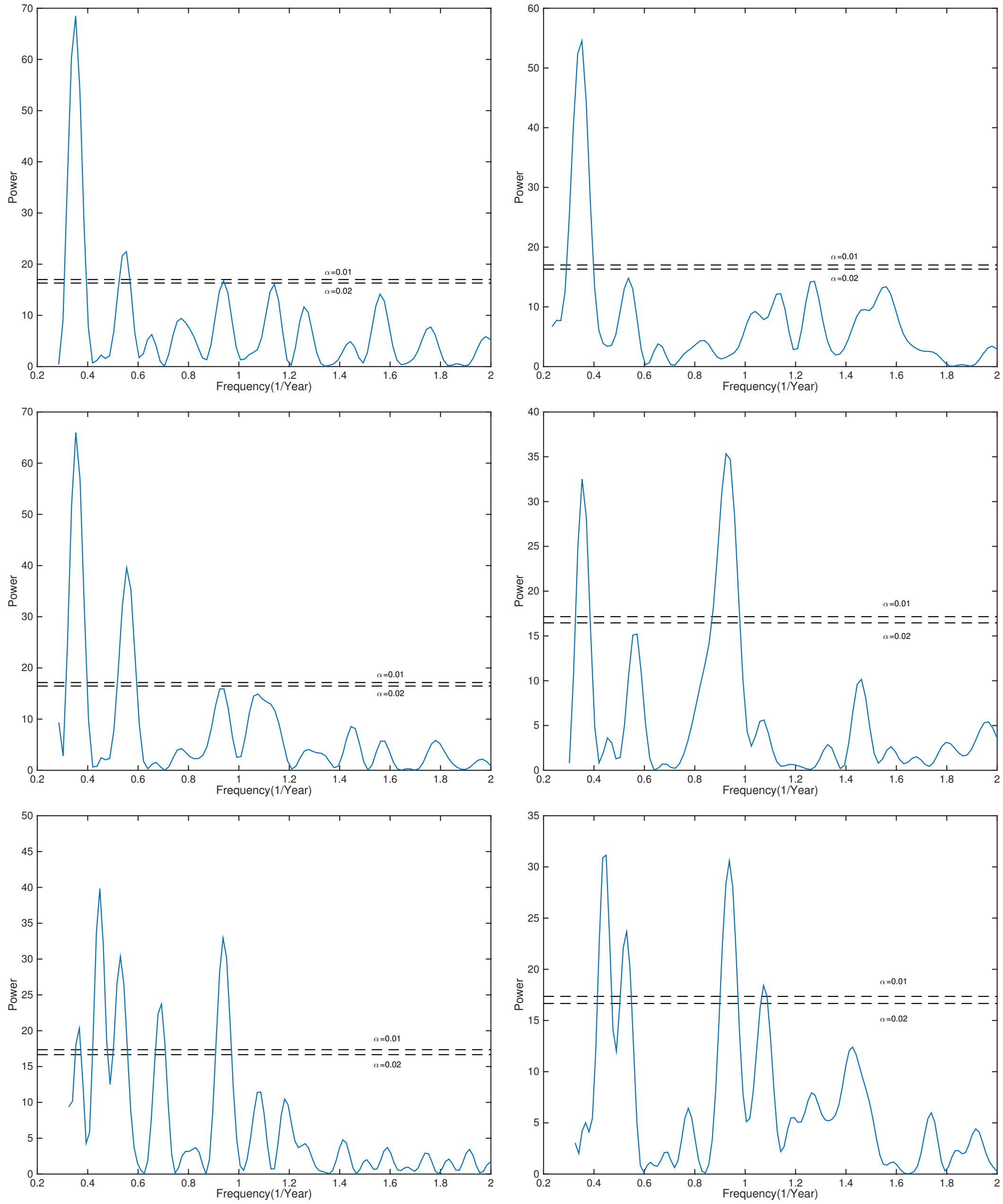

Fig. 3 *Left column*: LSPs of the daily MPSI during cycle 21 (*top panel*), cycle 22 (*middle panel*) and cycle 23 (*bottom panel*). *Right column*: The same as the left column but for daily MWSI. In each panel, the x-axis indicates the range of examined frequencies, the y-axis displays the power corresponding to each frequency, and the two *dashed horizontal lines* show the 0.01% and 0.02% significance level, respectively.

Table 1 The periodicities (in years) of the daily MPSI and MWSI in solar cycles 20−24.

MPSI	-	3.44	2.71	2.32	2.10	1.87	-	0.94	0.92	0.88	-
MWSI	3.85	3.00	-	2.30	1.98	1.87	1.18	1.07	0.92	0.88	0.70

cycle, we analyze the mid-term periodicities of MPSI and MWSI in the ascending/declining phases of solar cycles 20−24. The LSPs of the daily MPSI and MWSI, respectively, in ascending/declining phases of solar cycles 20−24 are plotted in Figures 4 and 5. We examine the range of periodicities about 0.3−2 yr, and those periodicities which are statistically significant at the 99% and 98% confidence level are taken into account. The mid-term periodicities detected in Figures 4 and 5 are also given in Table 3.

Table 2 The periodicities (in years) of the daily MPSI and MWSI during solar cycles 21, 22 and 23.

cycle 21	MPSI	2.83	-	1.80	-	1.07	-
	MWSI	2.83	-	-	-	-	-
cycle 22	MPSI	2.83	-	1.80	-	-	
	MWSI	2.83	-	-	-	1.08	-
cycle 23	MPSI	2.72	2.23	1.88	1.44	1.07	-
	MWSI	-	2.23	1.88	-	1.07	0.93

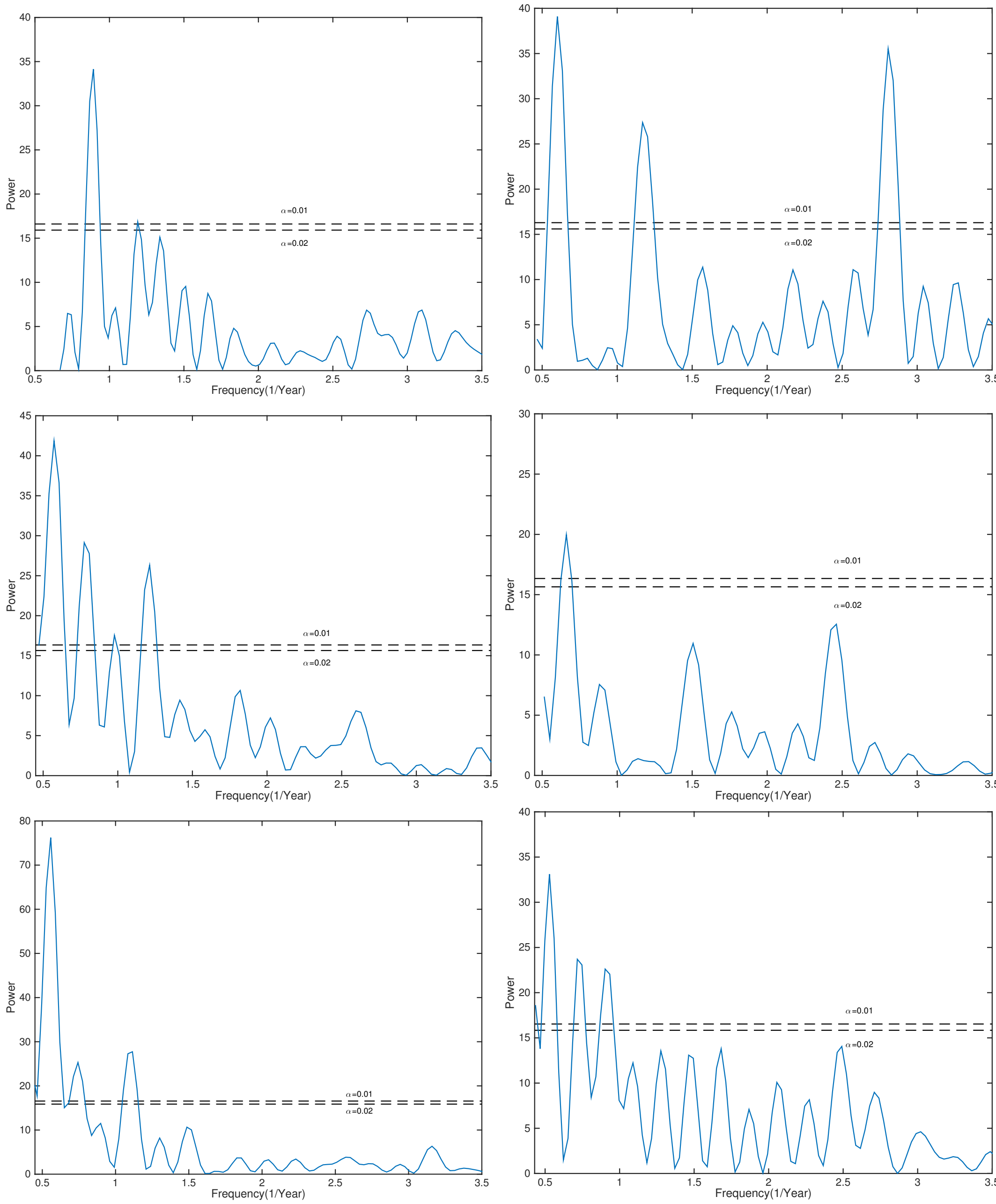

Fig. 4 *Left column*: LSPs of the daily MPSI in declining phases of solar cycles 20−23 ranked from top to bottom (continued on the next page), respectively. *Right column*: The same as the left column but for daily MPSI in ascending phases of solar cycles 21−24. In each panel, the x-axis indicates the range of examined frequencies, the y-axis displays the power corresponding to each frequency, and the two *dashed horizontal lines* signify the 0.01% and 0.02% significance level, respectively.

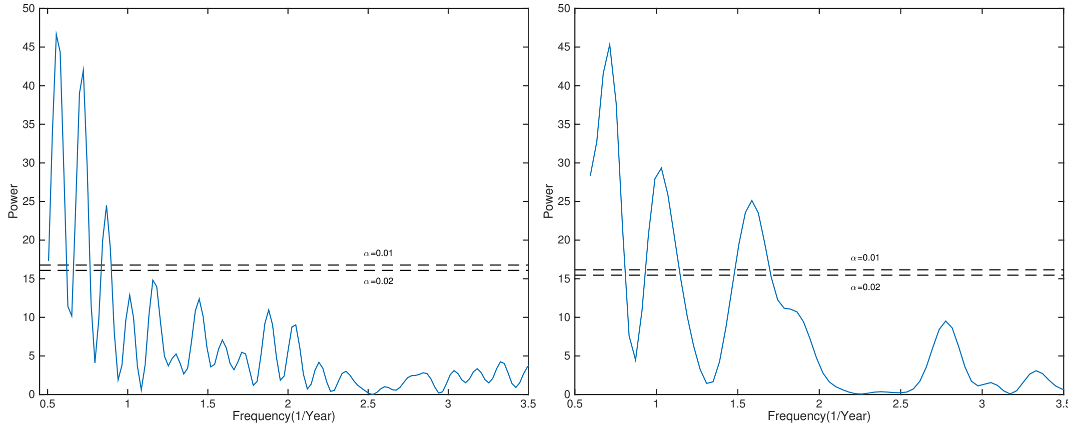

Fig. 4 —*Continued.*

Table 3 The periodicities (in years or days) of the daily MPSI and MWSI in ascending and declining phases of solar cycles 20−24.

Declining phase of cycle 20	MPSI	-		1.12	0.84		-	-	-	-
	MWSI	-	-	-	0.85	0.74	-	-	-	-
Ascending phase of cycle 21	MPSI	1.66	-	-	0.85	-	-	-	130 d	-
	MWSI	1.78	-	-	-	-	165 d	155 d	140 d	130 d
Declining phase of cycle 21	MPSI	1.74	1.28	1.02	0.82	-	-	-	-	-
	MWSI	1.61	-	0.96	-	0.65	-	-	-	-
Ascending phase of cycle 22	MPSI	1.51	-	-	-	-	-	-	-	-
	MWSI	-	-	1.07	-	-	-	-	-	-
Declining phase of cycle 22	MPSI	1.79	1.34	-	0.89	-	-	-	-	-
	MWSI	1.88	-	0.99	-	-	-	-	-	-
Ascending phase of cycle 23	MPSI	1.86	1.33	1.07	-	-	-	-	-	-
	MWSI	1.88	-	-	-	-	-	159 d	-	135 d
Declining phase of cycle 23	MPSI	1.80	1.33	1.10	-	-	-	-	-	-
	MWSI	1.77	-	1.07	0.90	-	-	-	-	-
Ascending phase of cycle 24	MPSI	-	1.35	0.98	-	0.63	-	-	-	-
	MWSI	-	-	-	0.93	0.61	-	-	-	-

3 DISCUSSION

In general, two indices (MPSI and MWSI), which represent the weak and strong magnetic field activity on the solar full disk, respectively, have many mid-term periodicities in the range of 0.3 to 4.5 yr. This means that both the weak and strong magnetic field activity has complex oscillations at the mid-term timescales. When we consider the entire time series of the daily MPSI and MWSI (spanning more than 40 yr), the periodicity 3.44 yr is found in MPSI, and the periodicities 3.85 and 3.00 yr are detected in MWSI. Xiang et al. (2014) indicated that the solar cycle for MPSI (10.83 yr) is obviously longer than that for MWSI (9.77 yr), while the mid-term periodicity for MPSI (3.44 yr) is obviously shorter than that for MWSI (3.85 yr), and so it is clear that these mid-term periodicities of MPSI (or MWSI) in the range of 3−4 yr should not be the 1/3 multiple harmonics of the solar cycle, but rather reflect the true oscillation signals of solar magnetic field activity. Moreover, periodic oscillation in the range of 3−4 yr is a global phenomenon, since the MPSI and MWSI reflect the magnetic field variation on the solar full disk. Berdyugina & Usoskin (2003) reported that the periods of 3.8 and 3.65 yr are detected in sunspot activity, which are somewhat consistent with the 3.85 yr periodicity in the MWSI. A 3.6 yr periodicity has been found by Knaack et al. (2005) in the total flux, and periodicities of 3.5−3.9 yr have been reported by Rao (1973) in spot group indices. Moreover, periodicities in the range of 3 to 4 yr were also detected in solar activity indices, such as in the soft X-ray flare index and flare indices (Vizoso & Ballester 1989; Joshi & Joshi 2004). These studies support the view that the mid-term periodicities of MPSI and MWSI in the range of 3−4 yr are the true oscillation signals of solar magnetic field activity.

At the timescale of 2 to 3 yr, not only are the periodicities of MPSI and MWSI detected when the entire time series of two indices are taken into account, but also these periodicities are found as well, when we analyze the two indices in each of the entire solar cycles 21−23. All the periodicities can be found in Figures 2 and 3 as well as in Tables 1 and 2, which indicate the typical periodicities of MPSI and MWSI are about 2.8 and 2.3 yr, and the two periodicities have small variations in different solar cycles. The period of 2−3 yr is also detected in many solar parameters, such as in the solar magnetic field (Obridko

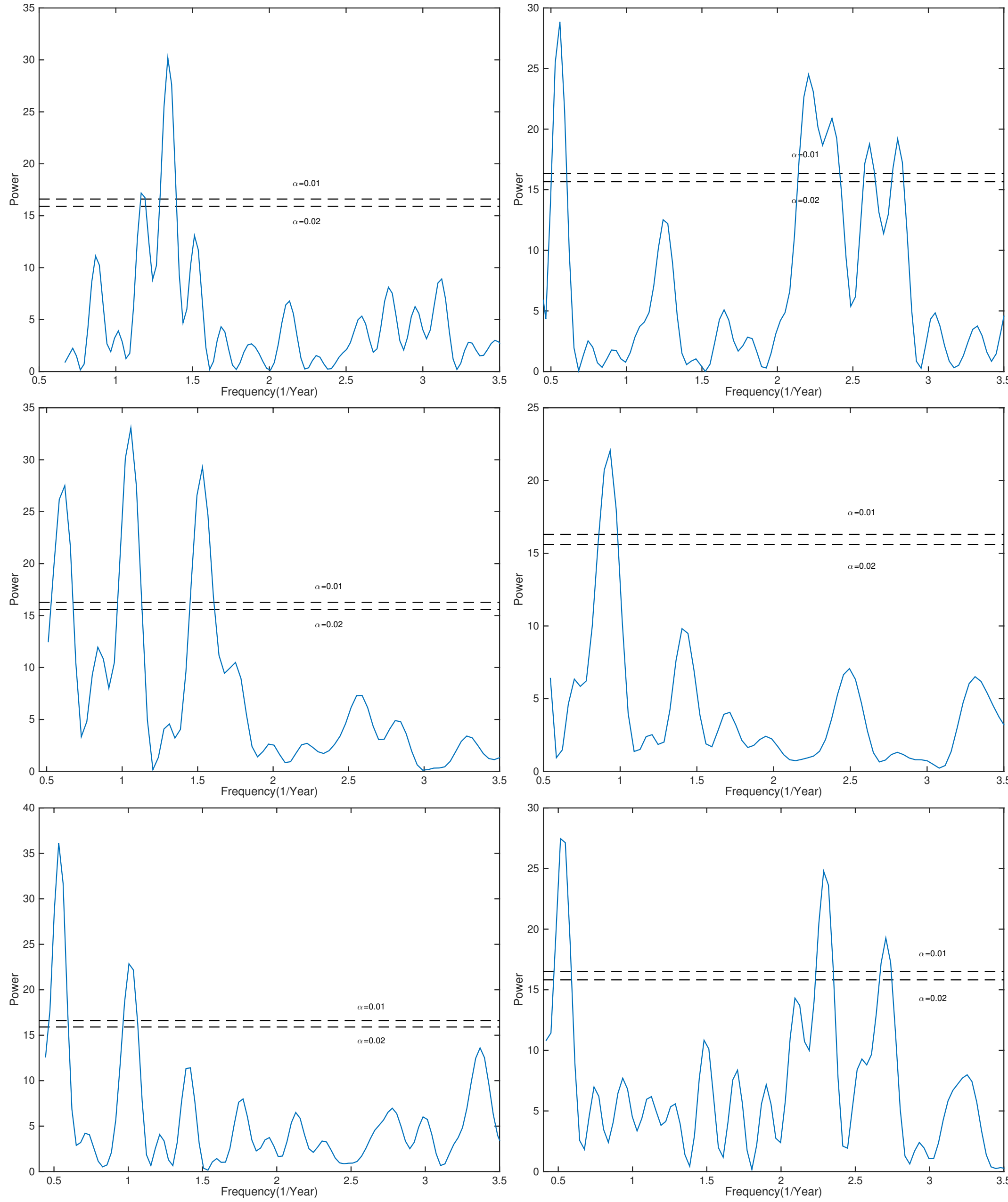

Fig. 5 *Left column*: LSPs of the daily MWSI in declining phases of solar cycles 20−23 ranked from top to bottom (continued on the next page), respectively. *Right column*: The same as the left column but for daily MWSI in ascending phases of solar cycles 21−24. In each panel, the x-axis indicates the range of examined frequencies, the y-axis displays the power corresponding to each frequency, and the two *dashed horizontal lines* show the 0.01% and 0.02% significance level, respectively.

& Shelting 2001, 2007), in the surface equatorial rotation rate (Javaraiah et al. 2009), in sunspots (Badalyan & Obridko 2011), in hemispheric flare activity (Deng et al. 2013), in solar radius (Qu & Xie 2013), etc. Bumba (2003) and Kane (2005) reported the quasi-biennial oscillations (QBOs) of solar magnetic field activity, which should be situated at the base of the solar convection zone. In addition, some studies reported that the QBOs are variable in period (with a range of 1.5−3.5 yr) between different solar cycles and within the same cycle (Bazilevskaya et al. 2000, 2014; Vecchio et al. 2012). Moreover, the global structure and spatio-temporal dynamics of the solar magnetic field studied by Vecchio et al. (2012) and Ulrich & Tran (2013) hinted that the QBOs are linked to the solar dynamo, and more advanced dynamo models may be required to explore the link between the QBOs and dynamo mechanism. Consequently, we infer that the mid-term periodicities of the MPSI and MWSI in the range of 2−3 yr are the QBOs, which may be linked to the solar dynamo.

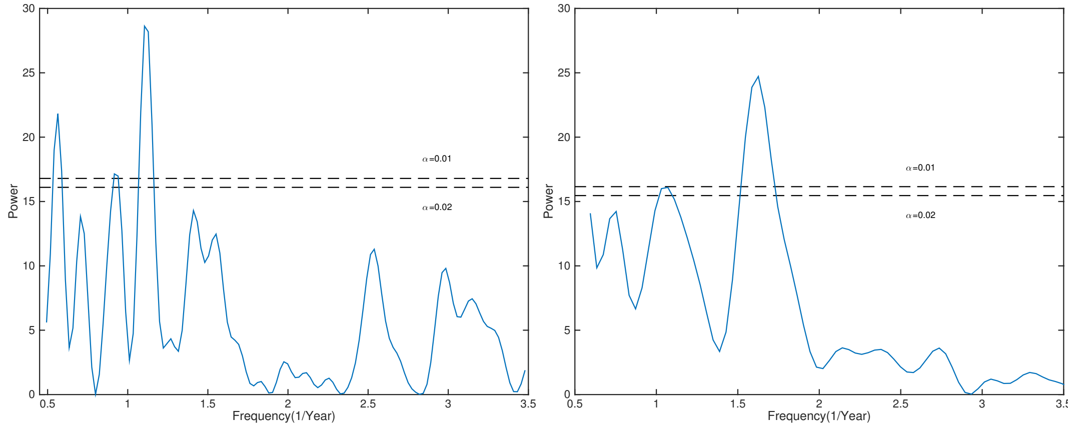

Fig. 5 —*Continued.*

The periodicity of around 1.8 yr in MPSI and MWSI is always detected when the two time series during more than 40 yr, each whole solar cycle 21−23 and the ascending/declining phases of cycles 20−24 are considered. Furthermore, this periodicity of the two indices is found to fluctuate around 1.8 yr within a very small amplitude in different solar cycles or phases, but disappears in some phases. Knaack et al. (2004, 2005) advised that the periodicity of 1.8 yr which was found in the north-south asymmetry of the unsigned photospheric flux should be derived from quasi-periodic oscillation on this timescale in the photospheric magnetic field of the Sun. Similarly, the periodicity of about 1.8 yr found in our study, which represents the quasi-periodic oscillation of weak and strong magnetic field activity on the solar full disk, should validate the results which are found in Knaack et al. (2004, 2005). Wang & Sheeley (2003) gave a viable explanation for the quasi-periodicities of magnetic field activity on the Sun in the range of 1−3 yr which is attributed to the stochastic interaction of the local fields and meridional flows. However, the periodicity of around 1.8 yr in the two indices is almost detected in each of the entire solar cycles 21−23 or the ascending and declining phases of cycles 21−24, and it is evident that this period of MPSI (MWSI) is not a random occurrence. On the other hand, the multitudinous mid-term periodicities of magnetic field at the solar surface, which have been suggested to be called "Rieger and similar Rieger-type" periodicities, are related to physical properties of Rossby-type waves and referred to as r-modes (Wolff & Blizard 1986; Wolff & Hickey 1987; Wolff 1996, 1998, 2000; Lou 2000; Dzhalilov et al. 2002; Knaack et al. 2005). Provost et al. (1981) defined the r-modes as globally coherent quasi-toroidal oscillations that are dominated by the Coriolis force, which in the limit of small scales reduce to Rossby waves. Ulrich (2001) studied the solar velocity features and found that there are long-lived torsional wave patterns in the solar surface velocity field, which resemble r-modes. On observation, Rossby-type waves show detectable features of large-scale velocity patterns and surface elevations. In a particular case, frequency estimates for r-modes are as follows (Lou 2000; Knaack et al. 2005)

$$\nu_m = \nu_s[\frac{|m|}{2} + 0.172\frac{3}{|m|}]^{-1} ,$$

where $\nu_s = 455$ nHz and m is the azimuthal order of the usual spherical harmonic indices (for details, see Lou 2000 and Knaack et al. 2005). A photospheric signature of long-period r-mode was observed by Kuhn et al. (2000) where 100 m high "hills" in the surface layer were spaced uniformly over the solar surface with a characteristic separation of approximately 90 000 km, and the m of this r-mode would be about 50. Using this function, the frequency estimate for this r-mode is $\nu_{m=50} = 18.2$ nHz, and the corresponding periodicity of $\nu_{m=50}$ is about 1.74 yr. This is very consistent with the periodicity of around 1.8 yr detected in the two indices within error limits. In particular, some periodicities of around 1.8 yr shown in the third column of Table 3, which are detected in different phases of solar cycles, are identical to this periodicity (1.74 yr) within error limits. Consequently, we advise that the periodicity of around 1.8 yr in MPSI and MWSI may be due to the the long-period r-mode signature in the surface layer. At least, the observation of a photospheric signature of a long-period r-mode (Kuhn et al. 2000) supports this interpretation. However, when we scan the periodicities of around 1.8 yr displayed in the third column of Table 3, the periodicities of the two indices are in the range of 1.51−1.88 yr, which is not always consistent with 1.74 yr within error limits. In this study, we only give a particular case for the frequency estimate of r-modes. In fact, there are complex and varied Rossby-type waves in the solar surface layer (for more details see Lou 2000; Knaack et al. 2005), which correspond to multitudinous periodicities of the solar magnetic field. Consequently, the periodicities of the two indices in the range of 1.51−1.88 yr should be due to the varied long-period r-mode signature in the surface layer.

The periodicity of around 1.3 yr is only detected in MPSI during some phases of solar cycles 20−24, and it disappears in some phases, such as in the declining phase of cycle 20, ascending phase of cycle 21, etc. (see Table 3). Moreover, this periodicity of MPSI is found to fluctuate around 1.3 yr within a very small amplitude in different phases, and so it can be considered as the same periodicity within error limits. Early studies concluded that the periodicity of nearly 1.3 yr in the solar rotation rate at the equator of the base of the convection zone should propagate to the solar surface and interplanetary space (1 AU and higher) (Prabhakaran Nayar et al. 2002; Mursula & Vilppola 2004). However, Howe et al. (2011) demonstrated that the 1.3 yr periodicity in the solar interior was intermittent and has not been observed since 2001, which is not consistent with the temporal distribution or evolution of the 1.3 yr periodicity in MPSI. If the periodicity of around 1.3 yr in MPSI is really related to variations in the internal rotation rate of the Sun, it is difficult to interpret that this periodicity is only detected in MPSI, and is also present after 2001. Knaack et al. (2005) indicated that the large-scale magnetic surges toward the poles in both hemispheres at intermediate latitudes during the maxima of solar cycles caused this periodicity. Indeed, it is well known that the meridional flows surge toward the poles or equator in different phases of solar cycles. Moreover, observations have shown that the meridional flows have been found to vary over the solar cycle as well as from one solar cycle to the next, and can extend all the way to the poles (Basu & Antia 2010; Hathaway & Rightmire 2010, 2011; Rightmire-Upton et al. 2012). The weak magnetic field activity on the solar full disk should indicate the signals which are related to meridional flows at the solar surface. Combining the earlier studies (Wang & Sheeley 2003; Ikhsanov & Ivanov 2004; Knaack et al. 2004, 2005; Obridko & Shelting 2007), we infer that the periodicity of around 1.3 yr in MPSI should be related to the meridional flows on the solar surface.

The periodicity of around 1 yr in MPSI (MWSI) is detected in the entire time series of the two indices, in each of the entire solar cycles 21−23 and in the ascending/decling phases of cycles 20−24. As shown in Tables 1, 2 and 3, the typical periodicity of MPSI (MWSI) is 1.07 yr, but it disappears in some phases. These periodicities of MPSI (MWSI) indicate the annual quasi-periodic oscillation of weak (strong) magnetic field activity on the solar full disk. It is well known that the nearly annual periodicity has a long history in solar physics, but it still remains mysterious in nature. Many papers reported that this periodicity exists in many solar activity indicators, such as in predominant polarity of the interplanetary magnetic field, in solar mean magnetic field, in total solar irradiance, etc. (Wilcox 1970; Wilcox & Scherrer 1972; Kotov 2006; Li et al. 2012; Xiang & Qu 2016), and a great many authors considered that the annual change in the Earth's heliolatitude causes the annual variation of these solar activity indicators. However, the periodicities of MPSI and MWSI detected in this study indicate that the annual quasi-periodicity disappears in some entire solar cycles or phases. If the annual periodicity of MPSI (MWSI) is really caused by the annual variation of the Earth's heliolatitude, it should be found in each of the entire solar cycles 21−23 or all phases. Hence, the disappearance of this periodicity indicates that the nearly annual periodicity of MPSI (MWSI) is not derived from the annual variation of Earth's heliolatitude. We consider Rieger-type waves, the frequency estimate of which for r-mode ($m = 31$) is $\nu_{m=31} = 29.3$ nHz, corresponding to periodicity of 1.08 yr. Indeed, this periodicity is consistent with the annual quasi-periodicity detected in MPSI (MWSI) (1.07 yr) as displayed in Tables 1, 2 and 3 within error limits. So, we infer that the nearly annual periodicity of MPSI (MWSI) should be due to the long-period r-mode signature ($m = 31$) in the surface layer.

Finally, the periodicities of about 0.63 (the range 0.61−0.65 yr), 0.74 and 0.85 yr (the range 0.82−0.89 yr), which correspond to about 230, 270 and 310 d respectively, are detected in MPSI or MWSI, but disappear in some phases of solar cycles 20−24. Moreover, the relatively short periodicities of 130, 135, 140, 155, 159 and 165 d are detected in MWSI, and the periodicity of 130 d is found in MPSI. These periodicities have a common feature in being close to multiples of the sidereal solar rotation period (25−26 d) at the equator, and they can be expressed as "Rieger-type" periodicities (Lou 2000; Knaack et al. 2005). Furthermore, the results in Zaqarashvili et al. (2010) and Gurgenashvili et al. (2016) also gave evidence that the Rieger-type periodicity should be longer than 200 d, though the early studies reported that this periodicity is about 154 d. Rieger-type periodicities are reported in many solar activity indicators, such as in the Zürich sunspot number (Wolff 1983), in solar diameter (Delache et al. 1985), in 10.7 cm radio flux (Lean & Brueckner 1989), in total solar irradiance (Pap et al. 1990), in daily counts of coronal mass ejection (CME) events (Lou et al. 2003), in sunspot area (Gurgenashvili et al. 2017), etc. Though Bai & Sturrock (1991) advised that a fundamental period could cause the excitation of subharmonic oscillations, this hypothesis would be seriously constrained by helioseismological data (Goode & Thompson 1992). Then, Lou (2000), Sturrock (2004) and Knaack et al. (2005) advised that the Rieger-type periodicities are due to Rossby-type waves. The detection and study of solar velocity features by Ulrich (1998, 2001) indicated the possibility of a Rossby wave origin. The interactions between torsional oscillation and large scale convection cause these waves on the solar surface, and also determine the rate of their variation. Moreover, these waves may be related to the solar dynamo since the torsional oscillations are closely connected to the latitude of magnetic activity. Similarly, the most promising explanation for the Rieger-type periodicity given by Zaqarashvili et al. (2010) indicated that it should be connected to magnetic Rossby waves in the solar tachocline. Owing to the differential rotation and toroidal magnetic field, the instability of magnetic Rossby waves in the dynamo layer is triggered, which leads to the quasi-periodic emergence of magnetic flux. Hence, these Rieger-type periodicities detected in MPSI and MWSI are also related to instability of the magnetic Rossby wave in the solar tachocline. Moreover, the Rieger period of around 155 d is only present in MWSI during cycles 21 and 23. Though some studies argued that the Rieger period disappeared after cycle 21 (Oliver et al. 1998; Ballester et al. 2002), our findings give evidence that the Rieger period is present in cycle 23. Ballester et al. (2004), Knaack et al. (2005) and Gurgenashvili et al. (2017) also indicated that the Rieger period is detected in cycle 23.

4 CONCLUSIONS

MPSI and MWSI, which have been measured at the MWO since the 1970s, and which indicate the weak and strong magnetic field activity on the solar full disk, respectively, are used to systematically analyze the mid-term periodicities of solar full disk magnetic fields using the LSPs as well as to determine the cause of these mid-term periodicities.

Multitudinous mid-term periodicities are detected in MPSI and MWSI on timescales of 0.3 to 4.5 yr, and these periodicities are found to fluctuate around several typical periodicities within small amplitudes in different solar cycles or phases. The periodicity 3.44 yr is found in MPSI, and the periodicities 3.85 and 3.00 yr are detected in MWSI, which reflect the true oscillation signals of solar magnetic field activity. The typical periodicities are 2.8, 2.3 and 1.8 yr in MPSI and MWSI, and possible mechanisms for these periodicities are discussed. The 2.8 and 2.3 yr periodicities are the solar QBOs and may be connected with the base of the solar convection zone, and the 1.8 yr periodicity should be due to the long-period r-mode signature in the surface layer. The 1.3 yr periodicity is only detected in MPSI; our analysis infers that it should be related to the meridional flows on the solar surface. The typical annual periodicity of MPSI and MWSI is 1.07 yr, which is not derived from the annual variation of the Earth's heliolatitude. Several periodicities shorter than 1 yr are found in MPSI and MWSI, which are considered to be Rieger-type periodicities.

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References

Akioka, M., Kubota, J., Ichimoto, K., Tohmura, I., & Suzuki, M. 1987, Sol. Phys., 112, 313
Badalyan, O. G., & Obridko, V. N. 2011, New Astron., 16, 357
Bai, T., & Sturrock, P. A. 1991, Nature, 350, 141
Ballester, J. L., Oliver, R., & Carbonell, M. 2002, ApJ, 566, 505
Ballester, J. L., Oliver, R., & Carbonell, M. 2004, ApJ, 615, L173
Basu, S., & Antia, H. M. 2010, APJ, 717, 488-495
Bazilevskaya, G. A., Krainev, M. B., Makhmutov, V. S., et al. 2000, Sol. Phys., 197, 157
Bazilevskaya, G., Broomhall, A.-M., Elsworth, Y., & Nakariakov, V. M. 2014, Space Sci. Rev., 186, 359
Berdyugina, S. V., & Usoskin, I. G. 2003, A&A, 405, 1121
Broersen 2009, Practical Aspects of the Spectral Analysis ofIrregularly Sampled Data With Time-Series Models, IEEE Trans. Instrum. Meas. 58, 1380
Bumba, V. 2003, in ISCS Symp., Solar Variability as an Input to the Earth's Environment, ed. A. Wilson (ESA SP-535; Noordwijk: ESA), 3
Cadavid, A. C., Lawrence, J. K., McDonald, D. P., & Ruzmaikin, A. 2005, Sol. Phys., 226, 359
Chapman, G. A., & Boyden, J. E. 1986, ApJ, 302, L71
Christensen-Dalsgaard, J. 2007, Convection in Astrophysics, Proceedings of IAU Symposium 239, eds., Kupka, F., Roxburgh, I., & Chan, K., 393
de Waele, S., & Broersen, P. M. T. 2000, Error Measures for Resampled Irregular Data, IEEE Trans. Instrum. Meas., 49, 216
Delache, P., Laclare, F., & Sadsaoud, H. 1985, Nature, 317, 416
Deng, L. H., Gai, N., Tang, Y. K., Xu, C. L., & Huang, W. J. 2013, Ap&SS, 343, 27
Domingo, V., Ermolli, I., Fox, P., et al. 2009, Space Sci. Rev., 145, 337
Dzhalilov, N. S., Staude, J., & Oraevsky, V. N. 2002, A&A, 384, 282
Feng, S., Yu, L., Wang, F., et al. 2017, ApJ, 845, 11
Goode, P. R., & Thompson, M. J. 1992, ApJ, 395, 307

Gurgenashvili, E., Zaqarashvili, T. V., Kukhianidze, V., et al. 2016, ApJ, 826, 55
Gurgenashvili, E., Zaqarashvili, T. V., Kukhianidze, V., et al. 2017, ApJ, 845, 137
Hathaway, D. H., & Rightmire, L. 2010, Science, 327, 1350
Hathaway, D. H., & Rightmire, L. 2011, ApJ, 729, 80
Horne, J. H., & Baliunas, S. L. 1986, ApJ, 302, 757
Howard, R., Adkins, J. M., Boyden, J. E., et al. 1983, Sol. Phys., 83, 321
Howard, R., Boyden, J. E., & Labonte, B. J. 1980, Sol. Phys., 66, 167
Howe, R., Christensen-Dalsgaard, J., Hill, F., et al. 2000, Science, 287, 2456
Howe, R., Komm, R., Hill, F., et al. 2011, Journal of Physics: Conf.Ser., 271, 012075
Ikhsanov, R. N., & Ivanov, V. G. 2004, Multi-Wavelength Investigations of Solar Activity, 223, 629
Javaraiah, J. 2003, Bulletin of the Astronomical Society of India, 31, 317
Javaraiah, J., Ulrich, R. K., Bertello, L., & Boyden, J. E. 2009, Sol. Phys., 257, 61
Joshi, B., & Joshi, A. 2004, Sol. Phys., 219, 343
Kane, R. P. 2005, Sol. Phys., 227, 155
Knaack, R., Stenflo, J. O., & Berdyugina, S. V. 2004, A&A, 418, L17
Knaack, R., Stenflo, J. O., & Berdyugina, S. V. 2005, A&A, 438, 1067
Komm, R., Howe, R., Durney, B. R., & Hill, F. 2003, ApJ, 586, 650
Komm, R., Howe, R., & Hill, F. 2004, 35th COSPAR Scientific Assembly, 35, 1397
Kotov, V. A. 2006, Sol. Phys., 239, 461
Krivova, N. A., & Solanki, S. K. 2002, A&A, 394, 701
Kuhn, J. R., Armstrong, J. D., Bush, R. I., & Scherrer, P. 2000, Nature, 405, 544
Lean, J. 1990, ApJ, 363, 718
Lean, J. L., & Brueckner, G. E. 1989, ApJ, 337, 568
Li, K. J., Feng, W., Xu, J. C., et al. 2012, ApJ, 747, 135
Li, K. J., Kong, D. F., Liang, H. F., & Feng, W. 2014, AN, 335, 371
Li, K. J., Zhang, J., & Feng, W. 2017, MNRAS, 472, 289
Lomb, N. R. 1976, Ap&SS, 39, 447
Lou, Y.-Q. 2000, ApJ, 540, 1102
Lou, Y.-Q., Wang, Y.-M., Fan, Z., Wang, S., & Wang, J. X. 2003, MNRAS, 345, 809
McDonald, D. P., Cadavid, A. C., Lawrence, J. K., & Ruzmaikin, A. 2005, American Geophysical Union, Spring Meeting 2005, SP43B-05
Mendoza, B., Velasco, V. M., & Valdés-Galicia, J. F. 2006, Sol. Phys., 233, 319
Mursula, K., & Vilppola, J. H. 2004, Sol. Phys., 221, 337
Obridko, V. N., & Shelting, B. D. 2001, Astronomy Reports, 45, 1012
Obridko, V. N., & Shelting, B. D. 2007, Advances in Space Research, 40, 1006
Oliver, R., Ballester, J. L., & Baudin, F. 1998, Nature, 394, 552
Pap, J., Bouwer, S. D., & Tobiska, W. K. 1990, Sol. Phys., 129, 165
Parker, D. G., Ulrich, R. K., & Pap, J. M. 1998, SoPh, 177, 229
Prabhakaran Nayar, S. R., Radhika, V. N., Revathy, K., & Ramadas, V. 2002, Sol. Phys., 208, 359
Provost, J., Berthomieu, G., & Rocca, A. 1981, A&A, 94, 126
Qu, Z. N., & Xie, J. L. 2013, ApJ, 762, 23
Rao, K. R. 1973, Sol. Phys., 29, 47
Rightmire-Upton, L., Hathaway, D. H., & Kosak, K. 2012, ApJ, 761, L14
Scargle, J. D. 1982, ApJ, 263, 835
Sturrock, P. A. 2004, ApJ, 605, 568
Ulrich, R. K. 1991, Advances in Space Research, 11, 217
Ulrich, R. K., Webster, L., Boyden, J. E., Magnone, N., & Bogart, R. S. 1991, Sol. Phys., 135, 211
Ulrich, R. K. 1998, Structure and Dynamics of the Interior of the Sun and Sun-like Stars SOHO 6/GONG 98 Workshop Abstract, (Boston, Massachusetts), 418, 851
Ulrich, R. K. 2001, ApJ, 560, 466
Ulrich, R. K., & Tran, T. 2013, ApJ, 768, 189
Vecchio, A., Laurenza, M., Meduri, D., Carbone, V., & Storini, M. 2012, ApJ, 749, 27
Vizoso, G., & Ballester, J. L. 1989, Sol. Phys., 119, 411
Wang, Y.-M., & Sheeley, N. R., Jr. 2003, ApJ, 590, 1111
Wang, Y.-M. 2004, Sol. Phys., 224, 21
Wilcox, J. M. 1970, J. Geophys. Res., 75, 2587
Wilcox, J. M., & Scherrer, P. H. 1972, J. Geophys. Res., 77, 5385
Wolff, C. L. 1983, ApJ, 264, 667
Wolff, C. L., & Blizard, J. B. 1986, Sol. Phys., 105, 1
Wolff, C. L., & Hickey, J. R. 1987, Science, 235, 1631
Wolff, C. L. 1996, ApJ, 459, L103
Wolff, C. L. 1998, ApJ, 502, 961
Wolff, C. L. 2000, ApJ, 531, 591
Wolff, C. L., & Mayr, H. G. 2004, ApJ, 606, L163
Xiang, N. B., Qu, Z. N., & Zhai, Q. 2014, AJ, 148, 12
Xiang, N. B., & Kong, D. F. 2015, AJ, 150, 171
Xiang, N. B., & Qu, Z. N. 2016, AJ, 151, 76
Xu, J. C., & Gao, P. X. 2016, ApJ, 833, 144
Zaqarashvili, T. V., Carbonell, M., Oliver, R., & Ballester, J. L. 2010, ApJ, 709, 749