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Periodicity of the solar radius revisited by using empirical mode decomposition and the Lomb–Scargle method *

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Abstract Using the Hilbert–Huang transform and the Lomb–Scargle method, we investigate periodicities in the daily solar radius data during the time interval from February 1978 to October 1999 derived from Calern Observatory. The following prominent periods are found: (1) the rotation cycle signal; (2) several mid-term periods including 122, 162.9 and 225 days, annual-variation periodicities (319 and 359 days), quasi-triennial oscillations (3.46 and 3.94 years); (3) the 11-year Schwabe cycle, which is in anti-phase with solar activity. This result indicates that the strong magnetic field associated with the Sun has a greater inhibitive effect on the radius variation.

Key words: Sun: activity — Sun: solar radius — Sun: photosphere — Sun: data analysis

1 INTRODUCTION

Measuring the Sun's shape seems easy, but actually it is one of the most difficult tasks in astrometry because the Sun does not have a clear boundary like rocky planets do. China was the first country in the world to measure it, records of which date back to the Western Han Dynasty in about 1 B.C. The Zhou Bi Suan Jing took the most original approach to measuring the solar radius. Zhang Heng, an ancient Chinese mathematician and scientist, described the size of the Sun in his publication from A.D. 120 called The Spiritual Constitution of the Universe. His result showed the solar-disk diameter to be $31'59''$, which is about $2''$ less than the modern value. In the West, French scientist Jean Picard (1620–1682) is regarded as the pioneer of measuring the solar diameter. He observed the temporal

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variation of the solar diameter to determine the eccentricity of Earth's orbit (Thuillier et al. 2006). The solar radius has been measured systematically since the 19th century. Usually, the solar radius is defined as the distance from the center of the Sun to the outer boundary of the photosphere. The standard value of the solar radius, 959.63″ that was originally adopted by the IAU, was obtained by Auwers (1891).

From ancient times until now, a variety of instruments and different techniques have been used to measure the solar size: (1) the use of solar eclipses and planetary transits (Mercury and Venus), by timing the appearance and disappearance of Baily's beads or planetary crossings of the solar disk (Kilcik et al. 2009; Adassuriya et al. 2011; Sigismondi 2011); (2) meridian circle observations used in the early days of the Greenwich Royal Observatory (Gething 1955; Eddy & Boornazian 1979); (3) drift-scan technology which measures the time with which the solar image drifts across a reference point in the focal plane of a telescope (Wittmann 1997; Wittmann & Bianda 2000); (4) Danjon astrolabes which are mainly used for solar observations at Calern Observatory and the Tubitak National Observatory (Laclare et al. 1996; Golbasi et al. 2001); and (5) direct angular measurements from satellites like *Solar and Heliospheric Observatory (SOHO)* and *Picard*, and the balloon-mounted instrument Solar Disk Sextant (SDS) (Emilio et al. 2001; Egidi et al. 2006; Meftah et al. 2013), as well as ground-based angular measurements. By comparing different methods in terms of the number of observations, Kilcik et al. (2009) pointed out that transits of Mercury and Venus were used little per century; use of eclipse observations obtained no more than three measurements per year; meridian transit observations gave one solar radius data value per day; satellite measurements and drift-scan methods have been used to obtain a number of observations in one day. However, results of these different measurement methods have been inconsistent and contradictory. Some researchers have reported that the solar radius has shown a secular decrease (Eddy & Boornazian 1979), but other researchers have reported that the solar radius is stationary (Neckel 1995; Kuhn et al. 2004; Bush et al. 2010). The reason for the lack of agreement may arise from effects involving seeing and observer errors, observational wavelength and bandpass, differing instrument characteristics, etc. (Basu 1998; Reis Neto et al. 2003; Kuhn et al. 2004; Djafer et al. 2008).

Some researchers have found the solar radius varies over periods of tens of days to several years. The key to these findings is that the solar radius has been demonstrated to vary within rotation cycles (Moussaoui et al. 2001; Penna et al. 2002; Kiliç & Golbasi 2011) and an 11-year period (Laclare et al. 1996; Moussaoui et al. 2001; Qu & Xie 2013). Laclare et al. (1996), Moussaoui et al. (2001), Reis Neto et al. (2003), Kiliç et al. (2009) and Qu & Xie (2013) found that the solar radius displays some mid-term periods (0.3–6 years). However, regarding the phase relation between long-term variation of the solar radius and solar activity, evidence is inconclusive. Some papers (Sofia et al. 1983, 1985; Egidi et al. 2006; Kiliç & Golbasi 2011) suggested that the variation of the solar radius has an anticorrelation with solar activity, but the results found by Ulrich & Bertello (1995), Noël (2004) and Chapman et al. (2008) showed the opposite. Such variations are an important issue for understanding the static and dynamic structure of the solar interior and the solar atmosphere (Kiliç & Golbasi 2011). It is also believed that variability in the solar radius is critical for understanding mechanisms related to solar radiation, space weather and Earth's climate.

In this study, we use nonlinear time-frequency analysis methods to study the periodicity variations of the solar radius measured at the Calern Observatory from February 1978 to October 1999. Section 2 describes the observational data sets and analysis methods. Section 3 contains a summary of the main conclusions and a discussion.

2 OBSERVATIONS AND DATA ANALYSIS

2.1 Data

The observational data on the solar radius used in the present study come from the Calern Observatory. These data were measured by one observer with the same instrument (for details see

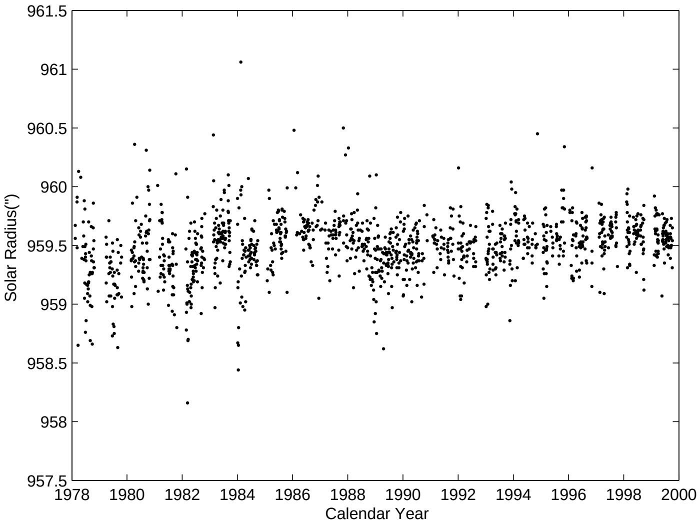

Fig. 1 Distribution of the daily average values of solar radius measurements recorded at the Calern Observatory from February 1978 to October 1999.

Laclare et al. 1996). The data set was compiled from 1975 to 2006, which covers the end of solar cycle 20 to the middle of solar cycle 23. Due to the weather, seasonal effects and instrument characteristics, the data have temporal gaps. The 1975 and 1976 observations are of an experimental nature and there are many discontinuities in the data after 1999. So, we choose daily data from February 1978 to October 1999 which cover more than two solar cycles. Usually, the daily data were obtained from a set of replicated observations (1–21 times) every day. Outliers have already been rejected from the data used here by applying the Dixon criterion (Dixon 1950) (for details see Qu & Xie 2013). The data set used in our analysis can be seen in Figure 1.

2.2 Hilbert–Huang Transform

The temporal and spatial behavior of solar-activity indicators is nonlinear and non-stationary in nature, and it is inappropriate, even incorrect, for recognizing the complex processes by means of traditional linear techniques such as the fast Fourier transform (Li et al. 2011; Gao et al. 2012; Deng et al. 2013a). Since the solar radius data are uneven and arise from nonlinear processes, it is necessary to adopt appropriate analysis methods to detect their periodic components locally and adaptively. Usually, Fourier analysis is the most commonly used method to seek periodicities from periodic signals, but it needs the data to be linear and stationary. Hence, traditional Fourier analysis is not suitable for analyzing our solar radius data. In addition, non-uniform data with large gaps can generate false peaks in the power spectrum, and the ghost peaks can even be larger than the real components (Kiliç et al. 2009).

Empirical mode decomposition (EMD) is a time-frequency analysis technique which was specifically developed for analyzing non-stationary and nonlinear signals (Huang et al. 1998). It has been successfully applied in solar physics, e.g. the extraction of periodicity associated with the 27-day rotation and the 11-year Schwabe cycle, in which the extracted periodic components from the solar time series are consistent with well-known periodic components (Xu et al. 2008; Li et al. 2012; Deng et al. 2013b). The fundamental concept used in the EMD approach is to decompose an input signal into a finite set of oscillating functions, called intrinsic mode functions (IMFs), which are the intrinsic oscillating periodicities of the original signal. Essentially, EMD is an algorithm which decomposes a signal into a finite set of IMFs (Wu & Huang 2009). These IMFs are defined as functions which are symmetric about their local mean, and whose number of extrema and zero crossings are equal or differ by less than one. These IMFs are extracted by applying a sifting process to the signal, in which the sifting process iteratively removes the local mean from a signal to extract the various cycles present. The sifting process is performed until the signal satisfies the definition of an IMF (for details, see Huang et al. 1998; Barnhart & Eichinger 2011).

Actually, the considered time series contains several physically meaningful components with complex characteristics. Some weak signals may be submerged by the strong signals or background noise. However, these useful weak signals can be extracted and made obvious through IMFs, so it is more accurate to obtain characteristic information about the original signal by analyzing components of the IMFs. In the present paper, to better detect significant periodicities that exist in the time series describing the solar radius, we first use the EMD method to decompose the data sets into several IMFs and a trend, and then the Lomb–Scargle periodogram is utilized to search for significant periodicities in each of the IMFs.

2.3 The Lomb–Scargle Periodogram Analysis

The Lomb–Scargle periodogram (Lomb 1976; Scargle 1982) is an important tool in frequency analysis for unequally spaced data. It can overcome the problem of missing data. Suppose there is a time series $Y(t_i)$ having N data points $i = 1, 2...N$, with a mean $\bar{Y}$ and a variance σ^2, which can be respectively computed from expressions $\bar{Y} = 1/N \sum_{i=1}^{N} Y_i$ and $\sigma^2 = 1/(N-1) \sum_{i=1}^{N} (Y_i - \bar{Y})^2$.

Then the Lomb–Scargle periodogram of frequency $\omega = 2\pi f$ is defined by:

$$P_N(\omega) = (1/2\sigma^2) \times \left\{ \frac{\left[\sum_{i=1}^{N} (Y_i - \bar{Y}) \cos\omega(t_i - \tau)\right]^2}{\sum_{i=1}^{N} \cos^2 \omega(t_i - \tau)} + \frac{\left[\sum_{i=1}^{N} (Y_i - \bar{Y}) \sin\omega(t_i - \tau))\right]^2}{\sum_{i=1}^{N} \sin^2 \omega(t_i - \tau)} \right\},$$

where P_N is the exponential distribution. Here phase τ is defined by the relation

$$\tan(2\omega\tau) = \frac{\sum_i \sin 2\omega t_i}{\sum_i \cos 2\omega t_i}.$$

For all periods tested, P_N gives the normalized power. We are also interested in the significance of any peak in P_N. The false alarm probability (FAP; Scargle 1982; Horne & Baliunas 1986) for the period search is defined as the probability that at least one of the peaks is equal to or greater than z: $\mathrm{FAP}(Z > z) = 1 - (1 - e^{-z})^N$ $Z = \max_n P_N(\omega)$, where Z is the highest peak of all frequencies, and the probability that none of the given values is larger than Z is $(1 - e^{-z})$.

2.4 Analysis Results

Figure 2 displays the results of ensemble empirical mode decomposition (EEMD) analysis for the solar radius, which is decomposed into nine IMFs. IMF9 is a trend result. Then, the Lomb–Scargle method is used to calculate their periodicities in the first eight IMFs. We eliminate the trend because the data only span a length of 22 years, and at present exhibit no periodicity in the trend. Figure 3 shows their Lomb–Scargle plots. The calculated periodicities are larger than the corresponding tabulated values for all IMFs except for IMF1, indicating that most of the periodicities are found to be statistically significant.

The periodicities of 28.6 and 57 days are related to the rotation cycle and two multiple harmonics of the rotation period. They only exist in IMF2 and IMF3. Thus IMF2 and IMF3 are called the rotation-variation signal of the solar radius. The rotation period has also been obtained by several

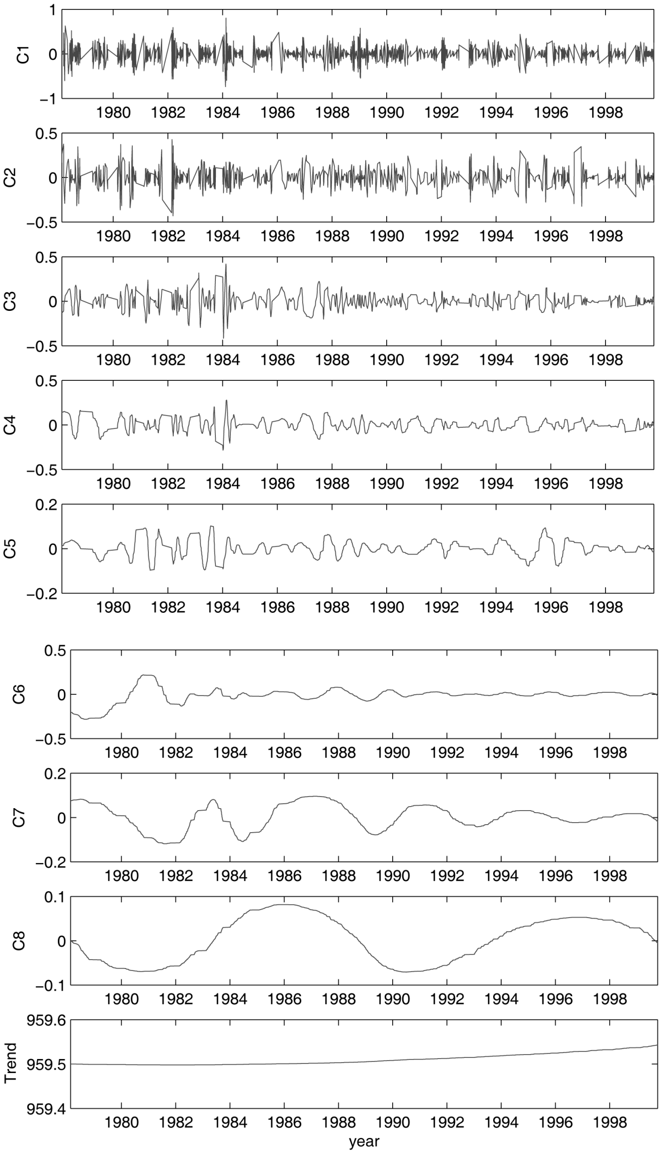

Fig. 2 Intrinsic mode functions (IMFs) of the solar radius, decomposed by EEMD.

prior studies. Using a Date Compensated Discrete Fourier Transform (DCDFT), Kiliç & Golbasi (2011) analyzed data obtained from 2000 February 26 to 2007 October 26 at TUBITAK National Observatory, and found that the solar radius had a significant 25.7-day period. The data obtained from 1975 to 1996 at Calern Observatory were analyzed by Egidi et al. (2006). One of the results showed a 27.7-day period. Using the CLEAN algorithm, Penna et al. (2002) studied the periodicities at the maximum of the solar activity cycle 23 with the daily data of the solar radius observed at Rio de Janeiro Observatory, and found that the radius has statistically significant rotational periods (24.5 days and 31.8 days). These values of rotation periodicities are quite different. Such a large variability has also been found in the coronal rotation period (Chandra & Vats 2011). The choice of different

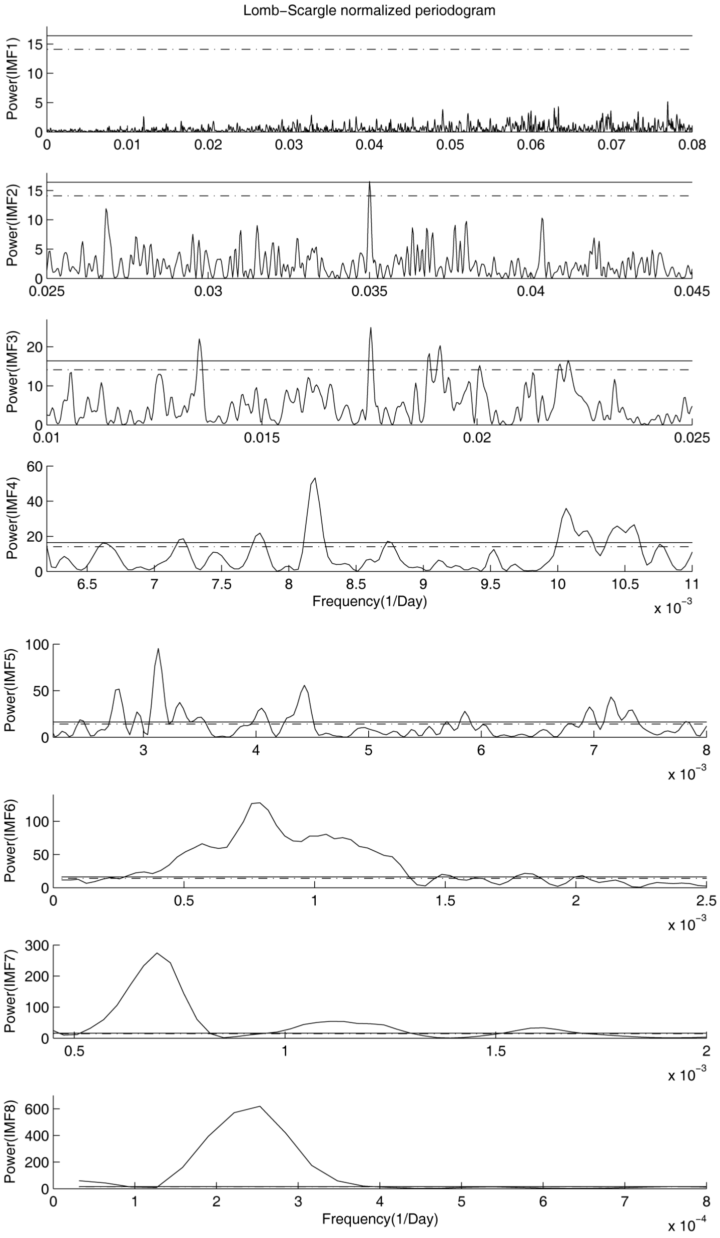

Fig. 3 Power spectra of IMFs 1 to 8 (from *top to bottom* respectively). Various significance levels are marked by a solid line (0.0001 per cent significance level) and dashed line (0.001 per cent significance level).

historical data and different data lengths should lead to the rotation period to varying slightly, which could cause its temporal variation and latitudinal differentiation.

The Lomb–Scargle spectra display several significant mid-term periodicities of about 73.9, 95.9, 99, 122, 225, 319 and 359 days and 3.46 and 3.94 years. Since the discovery of a 153-day period in γ-ray flare activity (Rieger et al. 1984), many solar activity indicators have been found to have midrange periods. Bai (2003) thought the regime between 27 days and 11 years can be called a "midrange" period, such as in the sunspot blocking function, 10.7 cm radio flux, sunspot numbers, coronal emission intensity (Deng et al. 2012), plage index (Lean & Brueckner 1989), sunspot areas and Zurich sunspot numbers (Oliver et al. 1992); and quasi-periodic oscillation in the photospheric magnetic field (Knaack et al. 2005); sunspot number, CaII area and K index, Lyman α, 2800 MHz radio emission, coronal green-line index, solar magnetic field (Kane 2005); total solar irradiance (Li et al. 2012); filament (Kong et al. 2014) and polar faculae (Deng et al. 2014). A spectral analysis of intermediate-term variations of the solar radius at TUBITAK National Observatory from 2000 February 26 to 2006 November 15 by Kiliç et al. (2009) also found extensive mid-term periodicities at 393.2, 338.9, 206.5, 195.2, 172.3 and 125.4 days. The 319 and 359 day periodicities correspond to the approximately one-year variation, which has been found earlier in the solar radius (Delache et al. 1985; Gavryusev et al. 1994; Moussaoui et al. 2001). The origin of the one-year periodicity may be caused by the influence of seasonal effects (Javaraiah et al. 2009). Thus, we suppose that the approximately one-year period is caused by Earth's orbital revolution. The periods of 3.46 and 3.94 years correspond to the so-called quasi-triennial 3-4 year oscillations. We should point out that some peaks in mid-term periods come from data gaps. The data gap of 46 days appears twice, and the mean value between it and adjacent gaps at 55, 58 and 59 days is 52.8 days. In this case, the peaks at 52.3 and 52.9 days, which are very close to 52.8 days, are ghost peaks. Similarly, the mean value of data gaps at 69, 74 and 75 days is 72.7 days, which is close to the peak at 73.9 days. So, the peak at 73.9 days is a ghost peak. The mean value of the data gaps at 90, 93, 95, 101 and 113 days is 98.4 days, which is close to peaks at 95.8 and 99 days. So, the peaks at 95.8 and 99 days are also ghost peaks. The mean value of the data gaps between 135 and 154 days is 141.3 days, so the peak at 139.8 days is a ghost peak. On the other hand, the significance levels of other peaks at 128.5, 136.2, 138.5, 144, 170.8, 246 and 300 days are lower than the eight peaks discussed above, but are over the highest FAP, so those peaks are less significant compared to other periodicities. Similar results were also found in TUG data from 2000 February 26 to 2006 November 15 (Kiliç et al. 2009).

The other important period is 10.8 years, and this has also been obtained through analyzing solar radius data acquired by other researchers (Laclare et al. 1996; Moussaoui et al. 2001; Qu & Xie 2013).

Figure 4 shows solar radius IMF8 and the yearly average sunspots areas. Both of them display an 11-year period. However, they are in an anti-phase relationship with each other. This result supports

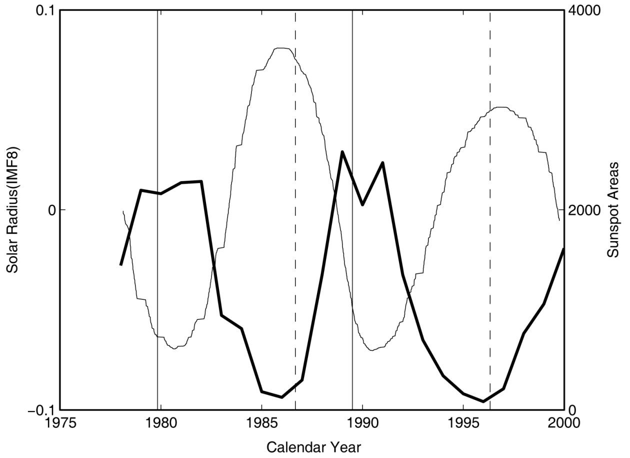

Fig. 4 Solar radius IMF8 (*thin line*, left ordinate) and yearly sunspot areas (*thick line*, right ordinate). The thin vertical dashed/solid lines indicate the minimum/maximum times of solar cycles.

the view of Lefebvre & Kosovichev (2005), Egidi et al. (2006) and Kiliç & Golbasi (2011). We can say that the solar radius shows the same periodic behavior as solar activity. Sunspot groups, sunspot areas, Wolf sunspot numbers and group sunspot numbers are the most direct forms of solar activity expression, and all of them display an 11-year Schwabe cycle (Li et al. 2002, 2005). In general, the stronger solar activity is, the more obvious the anti-phase relationship between radius and solar activity is found to be, which indicates that a strong magnetic field has a greater inhibitive effect on the variation of the radius than a weak magnetic field does. That is, a strong magnetic field has a greater inhibitive effect on the variation of the radius.

3 DISCUSSION AND CONCLUSIONS

In this paper, daily solar radius data taken at Calern Observatory between February 1978 and October 1999 are used to discuss the periods by means of the nonlinear EEMD method and Lomb–Scargle method. The EEMD method decomposes the time series describing the daily radius into physically meaningful components (IMFs), and the results of the analyzed IMFs by Lomb–Scargle are related to the rotational signal, mid-term signal and solar-cycle signal. Such results also agree with the conclusions of previously detected periodicities. The combination of the EEMD algorithm and the Lomb–Scargle method provides a local and adaptive description of the intrinsic cyclic components of the solar radius data, which are the results of nonlinear processes. The EEMD and Lomb–Scargle analyses of solar radius have revealed the following important results:

(1) More periodicities are found in the range of high frequencies than in low frequencies.
(2) The most important periods, the rotation cycle and the Schwabe cycle, exist in the time series.
(3) The rotation cycle being different is likely caused by solar temporal variation and latitudinal differentiation.
(4) The 11-year Schwabe cycle is in an anti-phase relationship with solar activity, which indicates that a strong magnetic field has a greater inhibitive effect on variation of the radius.

The two nonlinear methods return different kinds of details about periodicities. We have also compared our results with other solar radius data and types of solar indicator analysis. This discussion shows that our results are consistent with the results in various solar activity parameters reported by earlier researchers (ground-based measurements). However, a recent study based on data from *SOHO*/Michelson Doppler Imager (MDI) by Bush et al. (2010) shows that the solar radius does not exhibit any time variation over short- or long-term scales. Their result is not inconsistent with ground-based measurements, and they attributed misleading results from ground-based measurements of solar radius to effects from seeing. However, data obtained from the balloon mounted instrument SDS showed an anticorrelation between solar activity and solar radius, which is very similar to the Calern results (which are ground-based). Thus, effects from seeing are not the only factor leading to time variation. Djafer et al. (2008) compared radius data both from the ground and from outside of Earth's atmosphere; they concluded that a lack of consistent results in different solar radius measurements is not only due to atmospheric turbulence, but also dependent on instrumental characteristics and the spectral domain of observations for each investigation. In order to confirm whether disagreement in the rotation period of the ground-based solar radius data is caused by atmospheric seeing, Kiliç & Golbasi (2011) calculated both raw data with no correction and data that had been corrected for the effects of seeing (see Figs. 2 and 3). They found that both spectral peaks are significant and concluded that if atmospheric turbulence drives the ground-based solar radius measurements, both spectra cannot show similar peaks, so the rotation cycle may be related to the Sun itself. Spectral analysis of the Calern data by Moussaoui et al. (2001) obtained very sharp peaks with 27-day and 11-year periodicities compared with other periods, which are related to the solar rotation rate and magnetic activity. For this reason, they thought the results are not artifacts. Therefore, ground-based solar radius measurements are valuable for probing solar radius variations.

On the other hand, magnetic activity is considered to be the root cause of the solar cycle, and energy stored in the magnetic field plays a fundamental role in the energy balance of the Sun. Mechanisms arising from the magnetic field that drive periodicities in solar activity may also influence solar radius variations (Kiliç et al. 2009). As is well known, the surface magnetic fields are considered to play an important role in energy transfer from the interior to the surface by affecting convection. The magnetic field inhibits convection, causing a decrease in the efficiency of heat transport. Strong magnetic fields may lead to an increase in magnetic tension force. This would result in compressing the surrounding regions, leading to a shrinkage in the size of the Sun. So considering the whole magnetic field from a global perspective, when the magnetic fields are strong, the role of the magnetic field is obvious and it is possible to shrink the Sun's outer layers. But, at the same time, we should notice that even though the solar radius has been measured systematically for over 350 years, the main research has focused on the most recent 30 years of solar radius data. Thus, to see whether these periods will repeat and better understand the phase and amplitude relationship between the solar radius and sunspot activity, a longer-term and more-continuous data set will contribute to further confirming our conclusion. Also, more modern and powerful forecasting techniques that can be used to predict the sunspot cycle and solar radius are needed (Du & Wang 2011, 2012).

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