Multi-scale Oscillation Modes and Secular Trend Analysis of Astronomical Historic Archives

Yongyan Zuo[1], Yunfang Cai[2], Yuanyong Liu[1*], Xinan Tian[1], Jianmei An[1]
[1] Chongqing University of Arts and Sciences, Chongqing, China.
[2] Yunnan Observatories, Chinese Academy of Sciences, Kunming, China.

* Corresponding author. Tel.: 0086-023-49398559; email: 407837032@qq.com
Manuscript submitted March 8, 2019; accepted July 18, 2019.
doi: 10.17706/ijapm.2019.9.4.189-195

Abstract: Studies on astronomical historic archives are very important for understanding and promoting the progress of astronomy and astrophysics. For long-term solar data sets, they are the oldest topics in statistical astrophysics during the last four hundred years. To reveal the complex physical behavior of solar magnetic structures, a relatively novel time series analysis technique is applied here to investigate the multi-scale oscillation modes and the secular trend of yearly solar sunspot areas during the time interval from 1611 to 2005. Based on the empirical mode decomposition technique, the following results are found: 1) the time series of 395-year solar sunspot areas is decomposed into four intrinsic mode functions with different quasi-periodic oscillations, which could be understood four dynamic processes that have different periodic-scales; 2) for the secular trend of solar magnetic activity, the level of the Sun has a rapid decrease from 1611 to 1670, and then the activity level increases during the period of 1670-2005. The analysis results indicate that the utility of the empirical mode decomposition technique for the study of solar historic archives and could provide some very important information on the understanding of solar magnetic activity variations.

Key words: Time-frequency analysis, signal processing, empirical mode decomposition, intrinsic mode function.

1. Introduction

Solar sunspot is an astrophysical phenomenon that has been observed during the last four hundred years, and it is one of the most attractive features of solar magnetic activities [1]. Although it is not fully understood where the solar dynamo is situated, it is commonly accepted that solar dynamo should be seated near the bottom of convection zone of solar interior. Moreover, solar dynamo produces magnetic fluxes which create a lot of magnetic features, such as sunspots, plages, flares, prominences, small-scale jets, and coronal mass ejections [2]. Long-term observations of these magnetic structures have been measured in many astronomical observatories, and lots of magnetic indicators (sunspot areas, sunspot numbers, flare activity, coronal holes, filaments and prominences) could be applied to investigate the temporal and spatial variations of the Sun [3]. Solar activity cycle exhibits different lengths, strengths and amplitudes, it is thus very important to understand the physical cause of long-term temporal variations of the Sun [4].

In recent years, the study of statistical astrophysics has attracted considerable attention, because the temporal and spatial fluctuations in several scientific fields are very complicated and exhibit obvious nonlinear and non-stationary features [5]. Traditional time series analysis techniques, including the spectral and wavelet transform analysis, have many limitations in dealing with time-frequency signals [6]. Fortunately, many powerful and efficient techniques were developed for the analysis of astronomical signals. The empirical mode decomposition (EMD) method is a promising and powerful technique for studying nonlinear and non-stationary signals such as solar historic archives. Using the EMD method, a certain signal could be decomposed into a finite set of complete and orthogonal components called as intrinsic mode functions (IMFs), the key advantage of this technique over some other analysis approaches is the free from limitations on frequency and time resolutions [7], [8]. At present, this relatively novel analysis method has been extensively applied in lots of scientific fields, including the geomagnetic physics, pressure fluctuations, financial markets, and so on.

This work is organized as follows. Section 2 contains the observational data sets of yearly solar sunspot areas and the time series analysis method that is applied for astronomical archives. The multi-scale oscillation modes and the secular trend are revealed in Section 3. Finally, the conclusions and discussions of this work is presented in the last Section 4.

2. Data Archives and Analysis Approach

2.1. Astronomical Data Archives

Sunspots are the dark parts those are cooler (around 4500 K) than the surrounding area in the photosphere of the Sun, and they are as large as 5000 miles in diameter [9]. Solar magnetic fields are formed below the surface atmosphere and extend put into the corona which owns high temperature. An obvious feature of sunspot areas or sunspot numbers, which are the key indicators of solar magnetic activity, is the approximate 11-year cycle (sometime, from 9.5 years to 12.5 years) [10]. To this day, sunspot observations remain the one of the best indicators of strong magnetic fields with a few gausses, and they have been become an important subject of extensive research [11]. Of course, daily, monthly, and yearly sunspot areas and some other activity indicators were widely investigated by various analysis techniques in the past few decades. For example, auto-correlation analysis, periodic variation analysis, chaotic and multi-fractal analysis are applied to provide an elegant statistical feature of nonlinear dynamical processes of the Sun [12].

The yearly solar sunspot areas for the time interval from 1611 to 2005 used in the present work are public available in the website (http://www.gaoran.ru/database/esai/). The extended time series of solar activity indices (ESAI) is an important database that contains the observational, synthetic, and simulated data sets of solar magnetic fields [13]. ESAI data archives could be applied to study the temporal and spatial variations of sunspot areas, polar faculae, latitudinal distribution, and hemispheric asymmetry [14]. Here, the 395-year time series of solar sunspot areas is used to study the multi-scale oscillation modes and the long-term trend variation of solar magnetic activity. Fig. 1 display the temporal distribution of solar sunspot areas in the period 1611-2005.

2.2. Time-Frequency Analysis Approach

The EMD technique is an adaptive time-frequency analysis method for nonlinear time series [15]. Applying this approach, a given solar time series could be decomposed into several IMFs, which should be satisfied two conditions: i) the numbers of extrema and the numbers of zero crossings should be either equal or differ at most by one, at least in the whole data set of the analyzed time series; and ii) the mean of the envelope defined by the local maxima and that defined by the local minima is zero at any point [16]. Sometime, the amplitude modulations of the IMFs are very sensitive to local variations such as the random components removal or smoothed. Adding all the IMFs together with the residual trend reconstructs the original time series without information loss or distortion [17].

Many astronomical studies showed that the EMD technique is more efficient than the classical Fourier transform or wavelet decomposition that generally require a far larger number of modes to describe the comparable complicated data sets [18]. This work applied the free software of EMD method, which is available at http://rcada.ncu.edu.tw/research1.htm, provided by N.E. Huang and his co-authors. A careful application of the EMD technique could decompose solar time series into physically meaningful modes, namely multi-scale oscillation modes [19]. That is, the dominant IMFs derived from the original data set are associated with a large range of oscillations modes, such as short-term periodicities, mid-term periodicities, long-term periodicities, and the secular trend.

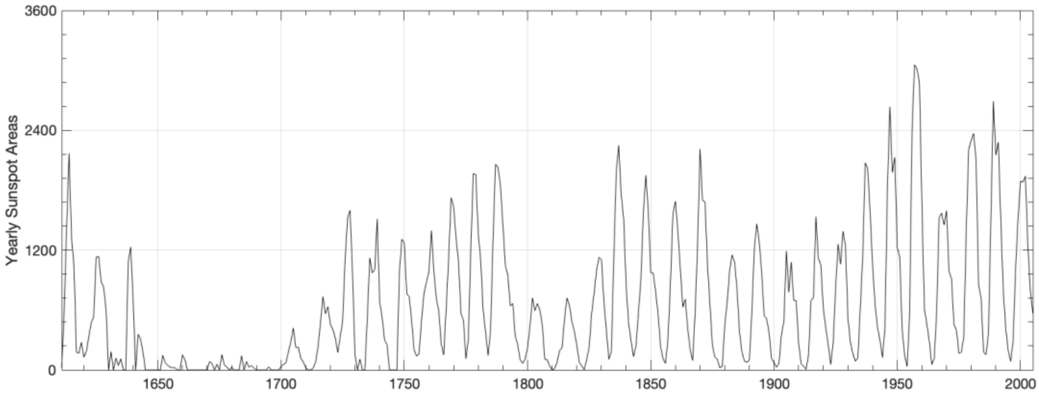

Fig. 1. Temporal distribution of solar sunspot areas during the time period from 1611 to 2005.

3. Results and Discussions

The EMD technique is applied to analyze the yearly time series of solar sunspot areas, and the results are shown in Fig. 2. From this figure, one can see that four IMFs are extracted from the original data set, and these four components represent different oscillation modes. The residual that represent the overall trend is shown in Fig. 3. Actually, the instantaneous frequencies of each IMF have different features, and each IMF mainly possesses a low instantaneous frequency than the preceding one, indicating the oscillation mode at higher IMF has a larger periodicity.

Solar magnetic activity fluctuates with time and exhibits a range of periods from scales of few years up to thousands of years as evinced from many proxies of solar magnetic fields. The dominant periodicity of the first IMF is associated with the typical periodicity near 11-year cycle of the Sun, which is attributed to the large-scale dynamo process operating in the solar interior, although the physical reason behind this periodicity has not fully understood. For the second IMF, the manly periodicity is calculated to be around 22 years, which is related to the solar magnetic cycle (when the polarity of solar magnetic fields is changed its sign every eleven years). Of course, the third IMF exhibits the 50-year periodicity, which could be considered as a relatively long-term period. The last IMF shows the 100-year periodicity, which is the long-term temporal variation of the Sun. It should be noted that these periodicities, including the 11years, 22 years, 50 years, and 100 years, are frequency observed in the solar time series and geomagnetic activity indicators. Sometimes, the analysis results of the EMD method are similar to other typical analysis techniques, such as wavelet multiple resolution analysis as applied in earlier studies. Therefore, the EMD approach decomposed the astronomical data archives into several meaningful modes provides confidence that this method is of significant utility.

To show the secular trend of solar time series, the length of the data archives should be long enough. The yearly time series of solar data archives is 395 years, so it is enough to extract its secular trend. From earlier studies, solar magnetic activity seems to have been a steady increase in the amplitude of solar activities, especially from solar cycle 6 onward. For example, the value of yearly mean sunspot numbers gradually increases during the period 1700-1975, and then decreases gradually from 1975 to 2015. From the extracted result of the EMD technique, the long-term trend of yearly sunspot areas could be obtained, and the result is displayed in Fig. 3. The secular trend could be calculated as the original time series subtracting the sums of IMFs 1 to 4, which have different oscillation periodicities.

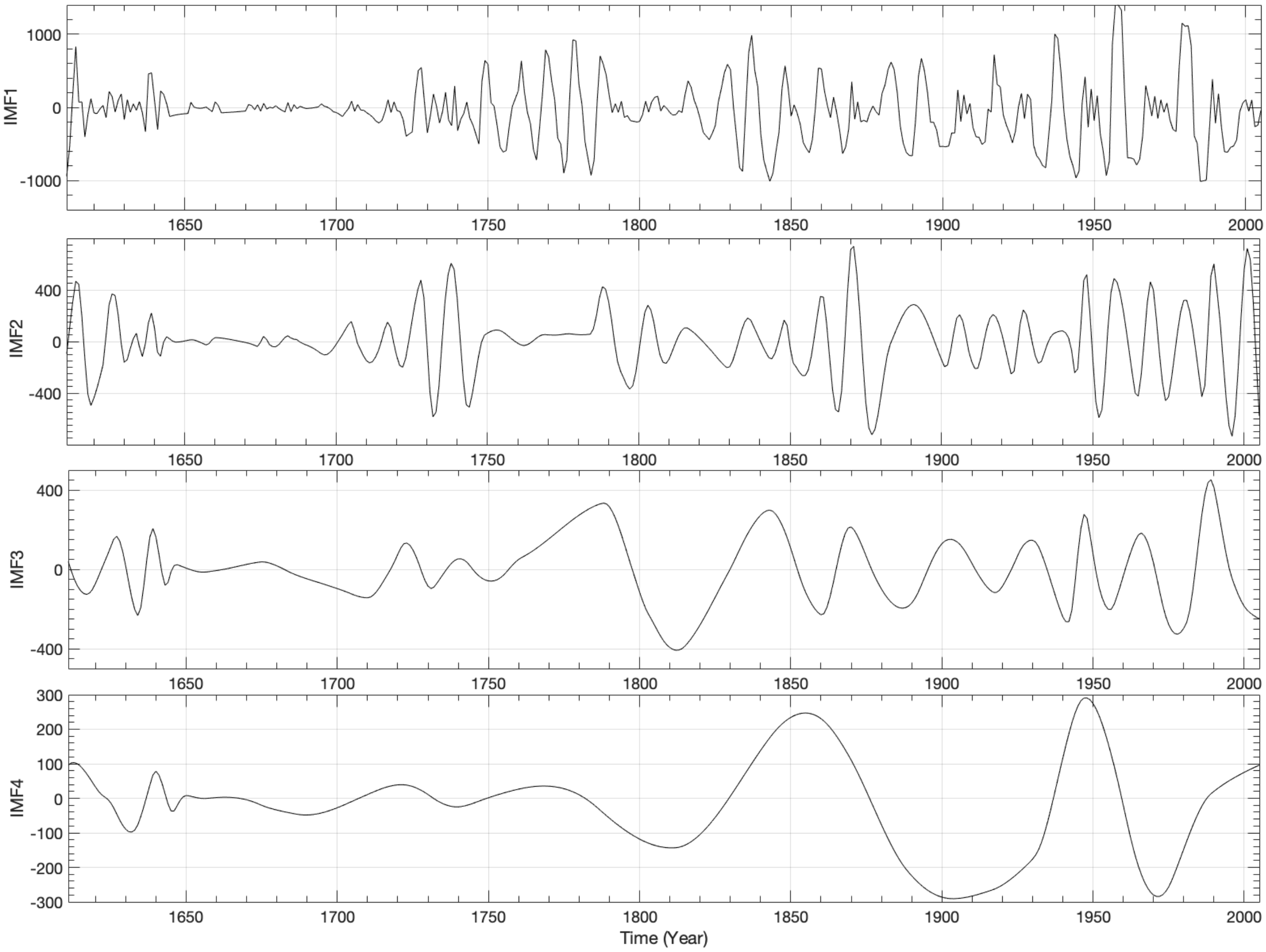

Fig. 2. The results of application of the EMD technique to the yearly time series of solar sunspot areas. Four IMFs extracted from the original data set are shown from the top panel to the bottom panel.

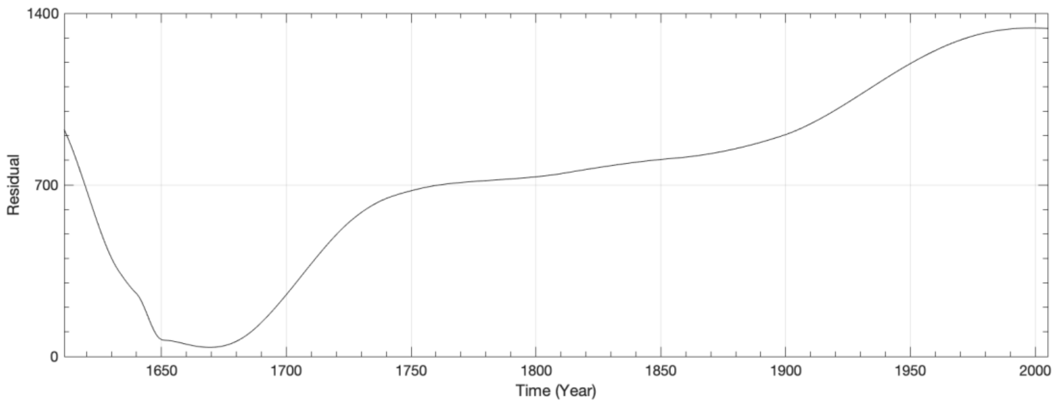

Fig. 3. The long-term trend of solar sunspot areas extracted from the EMD technique.

Based on Fig. 3, the level of the Sun has a rapid decrease from 1611 to 1670, and then the activity level increases during the period of 1670-2005, which could be understood as the long-term trend of solar magnetic activity, especially the geomagnetic variations. Actually, the certain period of about 70 years in the 17th century, namely from 1645 to 1715, is the Maunder minimum, because there are almost no sunspots in these years. The secular trend of yearly sunspot areas shown in Fig. 3 support that this special period is the most enigmatic feature of solar data archives.

4. Conclusion

The temporal and spatial dynamics of historical solar data archives in the time interval from 1611 to 2005 are analyzed by means of the data-adaptive and multi-periodic analysis called the EMD technique. The decomposition of astronomical time series into a finite of oscillatory modes traditionally relies on Fourier analysis method which can be considered to be a linear combination of sine and cosine functions. Our analysis results indicated that the yearly time series of solar sunspot areas have different oscillation modes with periodicities varying from 11 years to 100 years, which are frequency observed in the solar time series and geomagnetic activity indicators. Furthermore, for the secular trend of solar magnetic activity, the level of the Sun has a rapid decrease from 1611 to 1670, and then the activity level increases during the time period of 1670-2005.

So far, the physical mechanisms governing the solar magnetic activity cycle are still far from fully understood. Although lots of important information concerning this question could be retrieved from the variability of solar phenomena, including the diversity of multi-periodic processes. As solar sunspots are strong magnetic fields that related to various magnetic activities such as flares and filaments [20]. The analysis results could be further used to reveal the temporal and spatial variations of solar magnetic activity, and to recover the nonlinear dynamical processes of interior structure of the Sun.

From the analysis results, we could find that the EMD approach has the powerful ability to extract the periodic signals, the secular trend, and the existing noise from a given time series. That is, it is much more effective than the classical time series analysis techniques that are applied to analyze the data archives with linearity, normality, and stationarity. The analysis results derived from the EMD technique could provide more constraints on solar dynamo theories put forward by theoreticians to represent the oscillation modes of solar activity cycle. Some other analysis methods, such as proper orthogonal decomposition and multichannel singular spectrum analysis, are also very useful for extracting the common modes of variability of solar and stellar magnetic activities. In the near future, we will study the spatial and temporal behaviors of multi-periodic oscillations from multivariate data sets.

Acknowledgment

The authors would like to express their deep thanks to the staffs those provide the solar data archives and software for the public to use. This work is supported by the youth project of science and technology research program of Chongqing Education Commission of China (No. KJQN201801325).

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Yongyan Zuo was born on January 1983, in Wulong county, Chongqing, People's Republic of China. She graduated from the Physics Department of Chongqing University of Arts and Sciences in 2008 with a bachelor's degree. In the year of 2011, she graduated from Southwest University with a master's degree in agricultural science and technology organization and service. After graduation, she was engaged in archives management in Chongqing University of Arts and Sciences. Her research directions are data archives management framework analysis based on big data analysis.

Yunfang Cai took a first degree in Department of Physics in 2011 at the Tianshui Normal University. Then, she got the master degree and PhD in the years of 2014 and 2018, respectively, both at University Chinese Academy of Sciences. From June 2018 to present, she is a full-time assistant professor at Yunnan Observatories, Chinese Academy of Sciences. Her research interest includes big data analysis, astronomical technique and method, solar imaging and spectral observations, and so on.

Yuanyong Liu took a first degree in computer applied technology in the year of 1999, and got a master in computer software and theory in the year of 2007, both at the Chongqing University. Nowadays he is finishing his PhD program in the SEGi University in Malaysia. From 2007 to present, he is a full-time associate professor at Chongqing University of Arts and Sciences and has research work in several areas of big data, management information system, software engineer, and so on.

Xinan Tian was born on October 3, 1979 in Chongqing, People's Republic of China. He is currently an experimentalist in Chongqing College of Arts and Sciences. In July of 2013, he graduated from University of Electronic Science and Technology, and got the master degree of Engineering. His research interests contain pattern recognition, time-frequency analysis, astronomical image processing, education big data, network system, and so on. During the past 10 years, he has published several scientific papers on the above fields.

Jianmei An was born on October 8, 1981 in Shanxi, People's Republic of China. At present, she is working at School of Software Engineering, Chongqing University of Arts and Sciences. She graduated from Taiyuan University of Technology in July 2007 and got the master degree of engineering. Currently, her main research directions are astronomical big data, software engineering, and information system management, and so on. Also, the statistical analysis techniques such as time series analysis are her research interests.