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Periodicity in the most violent solar eruptions: recent observations of coronal mass ejections and flares revisited *

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Abstract Using the Hilbert-Huang Transform method, we investigate the periodicity in the monthly occurrence numbers and monthly mean energy of coronal mass ejections (CMEs) observed by the Large Angle and Spectrometric Coronagraph Experiment on board the Solar and Heliographic Observatory from 1999 March to 2009 December. We also investigate the periodicity in the monthly occurrence numbers of Hα flares and monthly mean flare indices from 1996 January to 2008 December. The results show the following. (1) The period of 5.66 yr is found to be statistically significant in the monthly occurrence numbers of CMEs; the period of 10.5 yr is found to be statistically significant in the monthly mean energy of CMEs. (2) The periods of 3.05 and 8.70 yr are found to be statistically significant in the monthly occurrence numbers of Hα flares; the period of 9.14 yr is found to be statistically significant in the monthly mean flare indices.

Key words: methods: data analysis — Sun: activity — Sun: coronal mass ejections (CMEs) — Sun: flares

1 INTRODUCTION

The well-known periodic variation of solar activity has been observed and studied extensively in the past using a variety of solar activity indices (Richardson et al. 1994; Krivova & Solanki 2002; Lou et al. 2003; Özgüç et al. 2003, 2004; Li et al. 2005; Joshi & Joshi 2005; Li et al. 2006; Joshi et al. 2006; Kiliç 2008; Li et al. 2010). As a result, the periodic variation of solar activity is now widely accepted. As is well known, the solar cycle is produced by a complex dynamo mechanism (Fang 2011). Searching for the periodicity of solar activity is important for building solar dynamo models, understanding solar activity and for their predictions (Du et al. 2006; Du 2006; Du et al. 2008; Xu et al. 2008; Du 2011). However, it is difficult to reach a consensus concerning the length of solar activity periods except for the Schwabe-period (approximately 11 yr). During the same solar

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cycle, it was found that a significant fraction of the periods for various indicators of solar activity are different (Joshi et al. 2006; Kiliç 2008).

Cho & Chang (2011) noted that a large amount of sunspot groups contributes little to the total area of sunspots. That is, the butterfly diagram is dominated by small sunspots. For example, 65% of groups (the smallest ones) contributes to only $\approx$ 10% of the total spotted area; on the other hand, 50% of the total spotted area is due to less than 10% of groups (the largest ones) (Ternullo 2007). This is because all groups are given an equal weight in the butterfly diagram, regardless of their temporal or spatial extension. Hence, statistical tests tend to be dominated by small solar activity events unless the temporal and spatial extensions are properly considered or the energy released in solar activity events is taken into account. The same problem should be noticed in investigating the periodic variations of solar activities.

Vourlidas et al. (2010) presented an extensive analysis of the first full solar cycle database of coronal mass ejections (CMEs) from the viewpoint of their mass and energy properties. Their measurements are incorporated in the online database of the Large Angle and Spectrometric Coronagraph (LASCO) principal investigator team at Naval Research Laboratory (NRL). This work provided us with a good source to investigate the periodicity in the CME energy. For each CME event, they compiled the evolution of the mass, potential energy, height and other properties as the CME progressed through the LASCO C2 and C3 fields of view. Here, we focus on the properties of the full CME sample rather than the evolution of a particular event. So we want to treat each event as an individual data point and therefore need to extract, for each event, a representative set of parameters at a single time frame. Vourlidas et al. (2010) pointed out that it is natural to assume that a representative point for each event is the time when the CME achieves its maximum mass and extracted parameters at that time frame. Thus, we also extract mass and potential energy at that time frame. Kinetic energy is obtained from the mass and linear speed (see Vourlidas et al. 2000 for details). The linear speed is obtained by linearly fitting the height-time measurements.

The calculations of the potential and kinetic energies of CMEs are directly made from the mass images. However, the values Vourlidas et al. (2000) used for the magnetic energy of those CMEs are only estimates because the magnetic field strengths in CMEs are unknown. Their estimates of the magnetic energy of CMEs are made on the basis of in situ measurements of magnetic clouds (MCs) near the Earth.

Huttunen et al. (2005) identified 73 MCs from the Advanced Composition Explorer (ACE) and WIND solar wind data during the seven-year period (1997–2003), or 0.90% of all the 8101 CMEs observed by LASCO on board the Solar and Heliographic Observatory (*SOHO*). From figures 3 to 6 of Vourlidas et al. (2000), we can find that the sum of the potential and kinetic energies of a CME is one order of magnitude higher than the magnetic energy of the CME for almost all cases that they studied when the CME achieves its maximum mass. Thus, we adopt the sum of the potential and kinetic energies of a CME as the total CME energy without consideration of its magnetic energy. In this paper, we investigate the periodicity in the monthly occurrence numbers and monthly mean energy of CMEs observed by *SOHO*/LASCO from 1999 March to 2009 December.

The quantitative flare index first introduced by Kleczek (1952), $Q = i \times t$, may be roughly proportional to the total energy emitted by the flare. In this relation, i represents the intensity scale of importance of a flare in Hα and t the duration in Hα (in minutes) of the flare (Özgüç et al. 2003, 2004). The present study also investigates the periodicity in the monthly occurrence numbers of Hα flares and monthly mean flare indices from 1996 January to 2008 December.

2 DATA

The time sequences of monthly CME counts and monthly mean CME energy are derived from a database of *SOHO*/LASCO produced by a consortium of NRL (USA), Max-Planck-Institut fuer Aeronomie (Germany), Laboratoire d'Astronomie (France) and the University of Birmingham

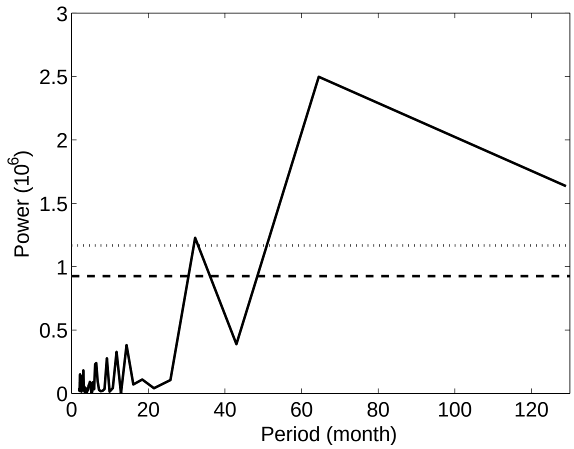

Fig. 1 Fourier transform spectra of the monthly numbers of CMEs from 1999 March to 2009 December. The dashed line represents the 95% confidence level and the dotted line is the 99% confidence level.

(UK)[1]. During the interval 1998 June to 1999 February, there were large data gaps. Thus, we investigate the periodicity in the monthly occurrence numbers and monthly mean energy of CMEs from 1999 March to 2009 December.

We use the monthly mean flare indices from 1996 January to 2008 December, which were calculated by T. Ataç and A. Özgüç from Bogazici University's Kandilli Observatory, Istanbul, Turkey and the data set is available to the general public from the anonymous ftp servers of the National Geophysical Data Center (NGDC)[2]. NGDC also prepares comprehensive solar flare listings in cooperation with the Department d'Astronomie Solaire et Planetaire, Observatoire de Paris, 92190 Meudon, France. The time sequence of monthly Hα flare counts is derived from these listings. The present study also investigates the periodicity in the monthly occurrence numbers of Hα flares and monthly mean flare indices from 1996 January to 2008 December.

3 RESULTS

Firstly, using subjective methods such as Fourier analysis, we investigate the periodicity in the monthly occurrence numbers of CMEs from 1999 March to 2009 December.

Figure 1 shows the Fourier transform spectra of the monthly numbers of CMEs. From Figure 1, we can find that the periods of 64.5 months (5.375 yr) and 32.25 months (2.6875 yr) are statistically significant at the 99% confidence levels in the monthly numbers of CMEs. However, Fourier analysis is subjective because it assumes a priori that the signal should have a constant period and a constant amplitude throughout the length of the time series. That is to say, it assumes that the signal is stationary. Thus, the period of 32.25 months may be a harmonic of the period of 64.5 months. In addition, the Fourier transform is linear. As is well known, these assumptions are not applicable to the solar cycle index.

The Hilbert-Huang Transform (HHT) is a data analysis tool which is able to extract the cyclic components from a signal. It is advantageous because it is able to analyze nonlinear and nonstationary data locally and adaptively (Huang et al. 1998). The HHT consists of two data analysis tools:

[1] *http://lasco-www.nrl.navy.mil/*
[2] *ftp://ftp.ngdc.noaa.gov/STP/SOLAR_DATA/SOLAR_FLARES/*

the empirical mode decomposition (EMD) and the Hilbert spectral analysis (HSA). EMD is an algorithm which decomposes an input signal into a finite set of oscillating functions, namely so-called intrinsic mode functions (IMFs), which are the intrinsic cycles of the original signal. These IMFs are extracted from the data themselves, and they are not restricted to have constant phases or amplitudes. An improved EMD algorithm called the ensemble EMD (EEMD) has been developed by Wu & Huang (2009), which utilizes this characteristic to extract robust and statistically significant IMFs. The HSA is a tool which calculates and displays the amplitude or energy (square of amplitude) contributions from the different extracted cyclic components as a function of time. Using these tools, the internal cycles of a signal, whether nonstationary or nonlinear, can be displayed and analyzed in the time domain or as time-frequency-energy spectra (Huang et al. 1998).

These IMFs are defined to be functions which are symmetric about their local mean, and whose number of extrema and zero-crossings are equal or differ at most by one (Huang et al. 1998). These IMFs are extracted from a signal using a process called sifting. The sifting process essentially iteratively removes the local mean from a signal to extract the various cycles present. The sifting process is performed until the signal meets the definition of an IMF (for details, please see Gao et al. 2011; Barnhart & Eichinger 2011).

To ensure that an IMF for EEMD contains a true signal, we test the statistical significance of IMFs based on the method proposed by Wu & Huang (2004, 2005).

(1) Calculate the energy of the IMFs. The energy of the nth IMF can be written as

$$NE_n = \sum_{j=1}^{N} [C_n(j)]^2, \tag{1}$$

where $C_n(j)$ is the nth IMF and N is the number of data points.

(2) Ascertain if any specific IMF contains little useful information, and assume that the energy of that IMF comes solely from noise.

(3) Use the energy level of that IMF to rescale the rest of the IMFs.

(4) Calculate the spread function of various percentiles of the theoretical reference white noise from

$$\rho(y) = C \exp\left\{ -\frac{N\bar{E}}{2}\left[1 - \bar{y} + \frac{(y - \bar{y})^2}{2!} + \frac{(y - \bar{y})^3}{3!} + ...\right]\right\}, \tag{2}$$

where $C = N^{N\bar{E}/2}$ and $y = \ln E$. Then we select the confidence-limit level (e.g. 99%).

(5) If the energy level of any IMF lies above the theoretical reference white noise line, we can safely assume that this IMF contains statistically significant information. If the rescaled energy level lies below the theoretical white noise, then we can safely assume that the IMF contains little useful information.

These tools will be used in order to analyze cycles apparent in monthly occurrence numbers and the monthly mean energy of CMEs observed by LASCO/*SOHO* from 1999 March to 2009 December, as well as monthly occurrence numbers of Hα flares and monthly mean flare indices from 1996 January to 2008 December.

3.1 The Periodicity in the Monthly Numbers and Monthly Mean Energy of CMEs

We plot the monthly numbers of CMEs as a function of time for the interval 1999 March – 2009 December, as shown in Figure 2.

The result of applying the EEMD method to the monthly numbers of CMEs is displayed in Figure 3(A). The monthly numbers of CMEs are decomposed into six IMFs and the resulting trend. We then tested the statistical significance of the six IMFs. The first IMF consists of a broadband spectrum; therefore it can be safely assumed to be pure noise and the energy level of the first IMF is used to rescale the energy level of other IMFs.

Figure 4(A) shows a scatter plot between the $\log_2$(mean normalized energy) and $\log_2$(mean period in months) of the six IMFs and a plot of the $\log_2$(mean normalized energy) as a function of $\log_2$(mean period in months) at the 0.05 and 0.01 significance levels (95% and 99% confidence levels), respectively. From Figure 4(A), we can find that the fifth IMF is statistically significant at the 99% confidence level indicating that the period of 5.66 yr is found to be statistically significant in the monthly numbers of CMEs. Other periods of 0.230 yr (84.1 d), 0.515 yr (188 d), 1.20 yr, 2.55 yr and 11.0 yr are below the 99% confidence level line, suggesting that these periods are the result of stochastic random noise and are not statistically meaningful.

Then we investigate the periodicity in the monthly mean CME energy from 1999 March to 2009 December using the HHT method. The result of applying the EEMD method to the monthly mean CME energy is displayed in Figure 3(B). The monthly mean CME energy values are decomposed into six IMFs and the resulting trend. We also tested the statistical significance of the six IMFs. The first IMF consists of a broadband spectrum; therefore it can safely be assumed to be pure noise and the energy level of the first IMF is used to rescale the energy level of other IMFs.

Figure 4(B) shows a scatter plot between the $\log_2$(mean normalized energy) and $\log_2$(mean period in months) of the six IMFs of the monthly mean CME energy and a plot of the $\log_2$(mean normalized energy) as a function of $\log_2$(mean period in months) at the 0.05 and 0.01 significance levels (95% and 99% confidence levels), respectively. From Figure 4(B), we can find that only the sixth IMF is statistically significant at the 99% confidence level indicating that the period of 10.5 yr is found to be statistically significant in the monthly mean CME energy. Other periods are below the 99% confidence level line, suggesting that these periods are the result of stochastic random noise and are not statistically meaningful.

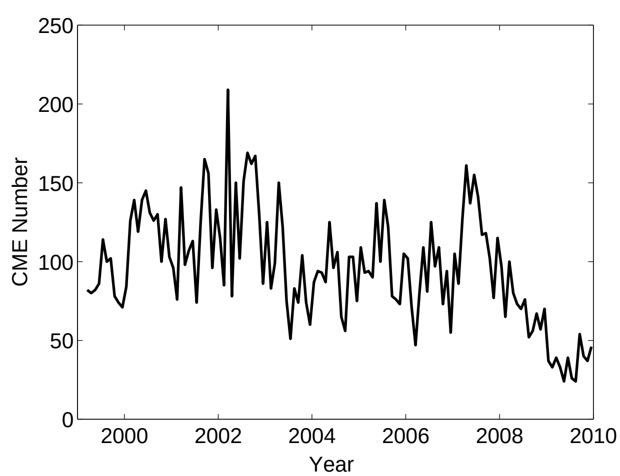

Fig. 2 Monthly numbers of CMEs for the interval 1999 March – 2009 December.

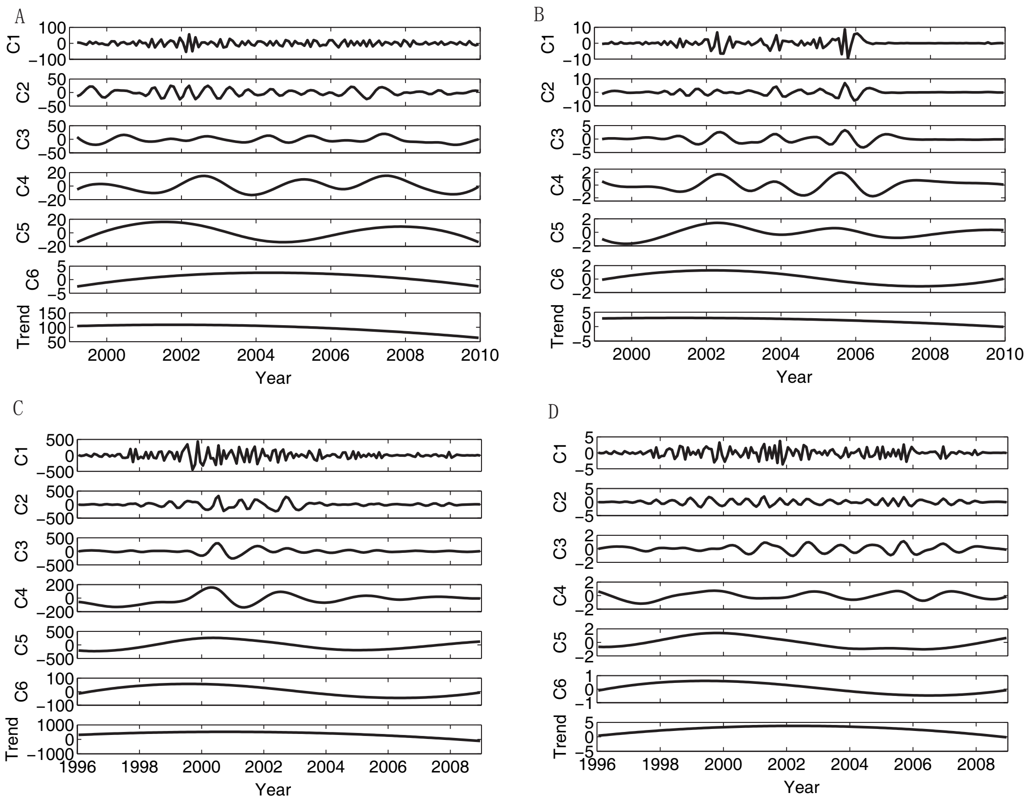

Fig. 3 EEMD decompositions of CME number (A), CME energy (B), flare number (C) and flare index (D). They are all decomposed into six IMFs and the resulting trend by the EEMD method.

3.2 The Periodicity in the Monthly Numbers of Flares and Monthly Mean Flare Indices

Using the HHT method, we also investigate the periodicity in the monthly occurrence numbers of Hα flares and monthly mean flare indices from 1996 January to 2008 December. The results of applying the EEMD method to the monthly occurrence numbers of Hα flares and monthly mean flare indices are displayed in Figures 3(C) and (D). The monthly occurrence numbers of flares and the monthly mean flare indices are all decomposed into six IMFs and the resulting trend. We also tested the statistical significance of the six IMFs of the monthly occurrence numbers of flares and the monthly mean flare indices. For the six IMFs of the monthly occurrence numbers of flares, the first IMF consists of a broadband spectrum, therefore it can be safely assumed to be pure noise and the energy level of the first IMF is used to rescale the energy level of other IMFs; for the six IMFs of the monthly mean flare indices, the first IMF also consists of a broadband spectrum, therefore it can also be safely assumed to be pure noise and the energy level of the first IMF is used to rescale the energy level of other IMFs.

Figures 4(C) and (D) show scatter plots between the $\log_2$(mean normalized energy) and $\log_2$(mean period in months) of six IMFs and plots of the $\log_2$(mean normalized energy) as a function of $\log_2$(mean period in months) at the 0.05 and 0.01 significance levels (95% and 99% confidence levels) for the monthly occurrence numbers of flares and monthly mean flare indices, respectively. From Figure 4(C), we can find that the fourth and fifth IMFs are statistically significant

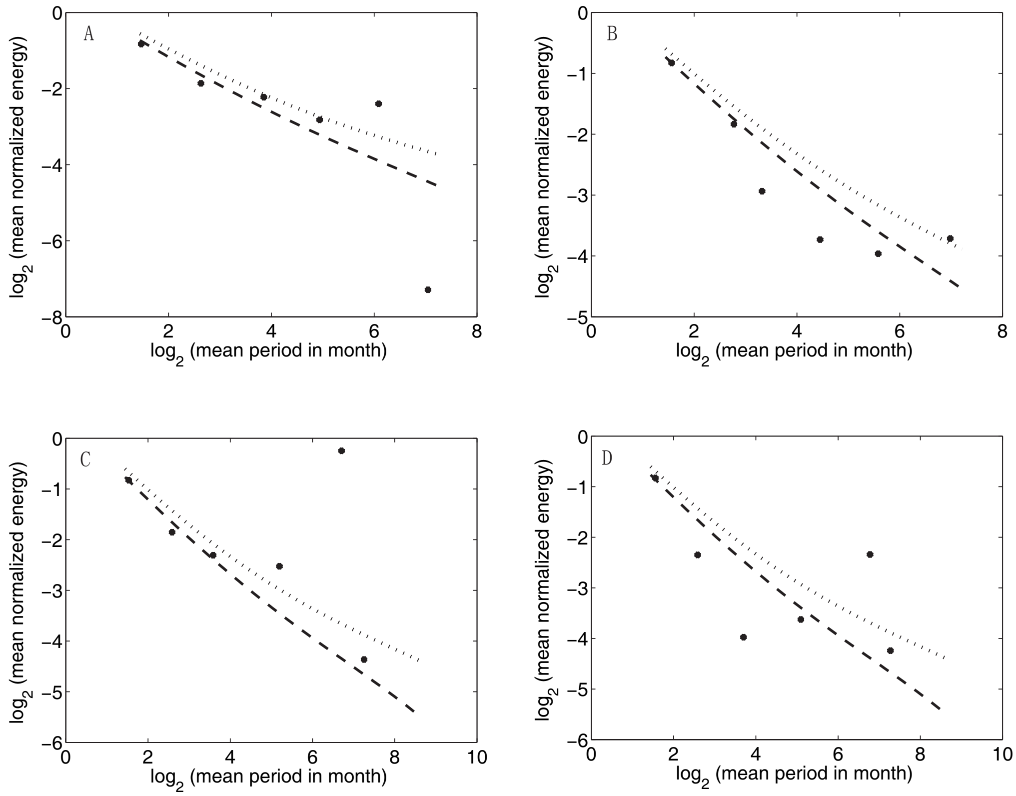

Fig. 4 Statistical significance tests of the six IMFs of the monthly numbers of CMEs (A), the monthly mean CME energy (B), the monthly numbers of flares (C) and the monthly mean flare indices (D). Each "target" sign in the four panels represents the $\log_2$ (mean normalized energy) of an IMF as a function of $\log_2$(mean period in months) of the IMF, ranging from the first IMF to the sixth IMF. The dashed lines represent the 95% confidence level and the dotted lines are the 99% confidence level.

at 99% confidence levels indicating that the periods of 3.05 and 8.70 yr are found to be statistically significant in the monthly occurrence numbers of flares. From Figure 4(D), we can find that the fifth IMF is statistically significant at the 99% confidence level indicating that the period of 9.14 yr is found to be statistically significant in the monthly mean flare indices.

4 CONCLUSIONS AND DISCUSSION

Using the HHT method, we investigate the periodicity in the monthly occurrence numbers and monthly mean energy of CMEs observed by LASCO/*SOHO* from 1999 March to 2009 December and the periodicity in the monthly occurrence numbers of Hα flares and monthly mean flare indices from 1996 January to 2008 December. The results show the following. (1) The period of 5.66 yr is found to be statistically significant in the monthly occurrence numbers of CMEs; the period of 10.5 yr is found to be statistically significant in the monthly mean energy of CMEs. (2) The periods of 3.05 and 8.70 yr are found to be statistically significant in the monthly occurrence numbers of Hα flares; the period of 9.14 yr is found to be statistically significant in the monthly mean flare indices.

The periods for monthly occurrence numbers of CMEs and flares are different: the period of 5.66 yr is found to be statistically significant in the monthly occurrence numbers of CMEs; the periods of 3.05 and 8.70 yr are found to be statistically significant in the monthly occurrence numbers of flares. Whereas solar activity has the 11-year sunspot number cycle and 22-year Hale magnetic cycle (Hale 1924) and probably an $\sim$80-year cycle (Gleissberg 1965) in the most prominent periodicities, short-term periodicities are often reported, notably $\sim$5-year, QBOs and QTOs (quasi-biennial 2–3 yr and quasi-triennial 3–4 yr oscillations), 1.7, 1.3, 1.0 yr, a few (5–7) months and a 27-day periodicity related to solar rotation (Pap et al. 1990; Obridko & Shelting 2001; Krivova & Solanki 2002; Kane 2003, 2005; Li et al. 2011). The period of 3.05 yr corresponds to the so-called QTO; the period of 5.66 yr corresponds to the $\sim$5 yr period; the period of 8.70 yr may correspond to the Schwabe period.

When we investigate the periodicity in monthly occurrence numbers of CMEs and flares, all events are given an equal weight, regardless of the energy released in solar activity events. As is well known, statistical tests tend to be dominated by small solar activity events unless the energy released in the solar activity events is well considered. Hence, we also investigate the periodicity in monthly mean energy of CMEs and monthly mean flare indices. As is well known, the flare index is roughly proportional to the total energy emitted by the flare. The period of 10.5 yr is found to be statistically significant in the monthly mean energy of CMEs, which corresponds to the Schwabe period; the period of 9.14 yr is found to be statistically significant in the monthly mean flare indices, which may correspond to the Schwabe period.

Two factors may contribute to explaining the discrepancy between the two statistically significant periods (10.5 yr and 9.14 yr) in monthly mean energy of CMEs and monthly mean flare indices. The first is that the length of *SOHO*/LASCO CME and flare index data used in this study is different: we investigate the periodicity in the monthly mean CME energy from 1999 March to 2009 December, while we investigate the periodicity in the monthly mean flare indices from 1996 January to 2008 December. The second factor is that the flare index is roughly proportional to the total energy emitted by the flare and we adopt the sum of the potential and kinetic energies of a CME as its total energy without consideration of the CME's magnetic energy.

Our results suggest that, during the same solar cycle, the periods for different solar activity (CME and flare) indices associated with the energy released in solar activity events may be similar; however, the periods for different indices (associated with the energy and the number of events) of the same solar activity (CME or flare) are different and the periods for different solar activity (CME and flare) indices associated with the number of events are different.

It must be pointed out that, in this paper, we adopt the sum of the potential and kinetic energies of a CME as its total energy without consideration of the associated magnetic energy when we investigate the periodicity in the monthly mean CME energy. Although the sum of the potential and kinetic energies of a CME is one order of magnitude higher than its magnetic energy for almost all cases that Vourlidas et al. (2000) studied when the CME achieves its maximum mass, ignoring the magnetic energy may introduce a source of error in this work. Admittedly, the results of this study are far from complete and it requires further research. Further efforts are being undertaken to confirm our results and uncover the physical mechanisms behind the periodicity of solar activity.

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