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Periodic behaviour of coronal mass ejections, eruptive events, and solar activity proxies during solar cycles 23 and 24

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ABSTRACT

We report on the parallel analysis of the periodic behaviour of coronal mass ejections (CMEs) based on 21 years [1996–2016] of observations with the SOHO/LASCO–C2 coronagraph, solar flares, prominences, and several proxies of solar activity. We consider values of the rates globally and whenever possible, distinguish solar hemispheres and solar cycles 23 and 24. Periodicities are investigated using both frequency (periodogram) and time-frequency (wavelet) analysis. We find that these different processes, in addition to following the ≈11-year Solar Cycle, exhibit diverse statistically significant oscillations with properties common to all solar, coronal, and heliospheric processes: variable periodicity, intermittence, asymmetric development in the northern and southern solar hemispheres, and largest amplitudes during the maximum phase of solar cycles, being more pronounced during solar cycle 23 than the weaker cycle 24. However, our analysis reveals an extremely complex and diverse situation. For instance, there exists very limited commonality for periods of less than one year. The few exceptions are the periods of 3.1–3.2 months found in the global occurrence rates of CMEs and in the sunspot area (SSA) and those of 5.9–6.1 months found in the northern hemisphere. Mid-range periods of ≈1 and ≈2 years are more wide spread among the studied processes, but exhibit a very distinct behaviour with the first one being present only in the northern hemisphere and the second one only in the southern hemisphere. These periodic behaviours likely results from the complexity of the underlying physical processes, prominently the emergence of magnetic flux.

1. Introduction

Solar eruptive phenomena such as flares, prominences, and coronal mass ejections (CMEs) are very energetic events which can significantly influence the interplanetary environment and space weather conditions (Chen, 2011; Webb and Howard, 2012). Characterizing their temporal evolution and, in particular, detecting possible periodic patterns can contribute to the understanding of the interactions at work and clarify their relationships and ultimately their physical origins.

Quasi-periodic variations have been found in essentially all physical indicators of solar activity extending from the 27-day synodic rotation period to the ≈11-year Schwabe Solar Cycle. Best examples are: i) the 154-day periodicity found in the temporal distribution of flares (Rieger et al., 1984) and subsequently in a variety of solar and interplanetary data (Richardson and Cane, 2005, and references therein), and ii) the 1.3-year periodicity detected at the base of the solar convection zone (Howe et al., 2000, 2007) and in sunspot area (SSA) and sunspot number (SSN) time series (Krivova and Solanki, 2002). These multiple periodicities collectively known as intermediate or mid-term quasi-periodicities together with those in the range of 0.6–4 years are often referred to as quasi-biennial oscillations (QBOs) and have been the subject of an in-depth review by Bazilevskaya et al. (2014). Barlyaeva et al. (2015) have recently shown that the radiance of the corona exhibits such QBOs sharing the same properties as those resulting from solar activity.

It has been proposed that these periodicities are in one way or the other related to the emergence of magnetic flux from the convection zone (Carbonell and Ballester, 1992; Ichimoto et al., 1985). Since for instance sunspot area, flares, erupting prominences, and coronal mass ejections are all some manifestation of this emergence – although their mutual relationships are not fully understood – it is conceivable that they all exhibit the same periodicities. The case of CMEs has only been recently considered since the continuous observations performed by the *Large Angle and Spectrometric Coronagraph* (LASCO; Brueckner et al.

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(1995)) onboard the *Solar and Heliospheric Observatory* (SOHO) since January 1996 offer the most appropriate source to investigate this question. Lou et al. (2003) examined the first four years of data around the peak of solar cycle (hereafter abbreviated to SC) 23 and based on Fourier power spectral analysis, they found significant power peaks at ten periods ranging from 33.5 to 358 days. Six of them exceeded two months, namely 66.25 days (2.2 months), 100 months (3.3 months), 110.8 days (3.64 months), 196 days (6.44 months), 272 days (8.9 months), and 358.3 days (11.8 months); note that they exclude the 154-day Rieger period found in flares. Lara et al. (2008) used the maximum entropy method to compute the power spectrum of a CME time series extending over a time interval of 10.75 years (1996.0–2006.75, that is essentially SC 23) and found ten periods ranging from 17.2 to 408.5 days. Those which exceed two months are: 93.84 days (3.1 months), 192.9 days (6.34 months), and 408.5 days (1.1 year) and also exclude the 154-day Rieger period. They also performed a time-frequency wavelet analysis in order to find when the different periodicities took place along the solar cycle. Contrary to these two studies based on occurrence rates, Vourlidas et al. (2010) investigated the mass rate (as a more relevant physical property) over a time interval of thirteen years (1996–2009) and applied the Lomb-Scargle spectral analysis to uncover the presence of a 6-month periodicity in the ejected mass from 2003 onward. In a subsequent erratum, Vourlidas et al. (2011) recognized an error in their previous analysis (failing to take into account the 180° periodic rolls of the SOHO spacecraft) and their re-analysis led to the disappearance of the 6-month periodicity. They did mention evidences of periodicity but gave no detail in their erratum. Choudhary et al. (2014) applied standard Fourier analysis to nearly six years (1999.25–2005.0) of CME occurrence rate resulting in a single period of 190 days (6.24 months) and wavelet power spectral analysis (also to flare and sunspot area time series) over a longer time interval of 13 years (1999.0–2012.0) that produced a significant time-frequency area peaking at 193 days and an additional period of about 154 days (≈ 5 months) during the rising phase of the current SC 24. Their claim that their 6-month period "is consistent with the findings of Vourlidas et al. (2010, 2011)" is somewhat surprising in view of the retraction by Vourlidas et al. (2011). Guedes et al. (2015) used wavelet analysis to identify patterns in CMEs, X-ray solar flares, and SSN in the interval [2000–2013]. The authors found a set of periods in the range of 16–1024 days in CME and X-ray flares appearing and disappearing at different phases of the solar cycle and an additional range of 128–256 days during the rising phase of SC 24 broadly consistent with the results of Choudhary et al. (2014).

The first aim of this work is to ascertain the existence of periodicities or quasi-periodicities in the CME activity by using a different database than used in the above articles and over a much longer time interval (almost two solar cycles), further evaluating and comparing different techniques of period searching. We also analyze both the occurrence and mass rates whereas past articles consider only the former rate except that of Vourlidas et al. (2010) which considers the mass but finally did not produce any result. The second aim consists in comparing the periodicities with those found in the temporal variations of different proxies of solar activity and of erupting processes known to be closely associated with CME, namely solar flares and prominences. Whereas the understanding of the origin of periodicities is presently out of reach as we shall later discuss, we may hope to shed some light on the underlying process (es) by comparing the results for different solar phenomena.

The article is organized as follows. Section 2 presents the ARTEMIS II catalog of CMEs, the solar proxies selected for comparison, and the solar flares and prominences data. Section 3 describes the methods used for period analysis. In Section 4, we broadly characterize the temporal evolution of the CME occurrence and mass rates (globally and by hemispheres), and then analyze in detail their short- and mid-term variations. Section 5 is devoted to the analysis of high-to mid-term frequency oscillations in proxies of solar activity and in the occurrence rates of flares and prominences. Finally, we discuss our results in Section 6 and summarize them in the conclusion (Section 7).

2. Observational data

2.1. Coronal mass ejections: the ARTEMIS II catalog

The aforementioned past investigations were all based on the catalog assembled by the Coordinated Data Analysis Workshop (CDAW) Data Center[1] which relies on visual detection by different operators. Limitations and biases inherent to this method (*e.g.* the varying cadence of the LASCO observations and arbitrary criteria resulting in the inclusion of many faint events after 2006) have been repeatedly pointed out (Wang and Colaninno, 2014; Webb and Howard, 2014) and may a-priori question the validity of this catalog for statistical studies and period searching. Our analysis is based on the ARTEMIS II catalog (Floyd et al., 2013) recognized as the most reliable among the different catalogs (Wang and Colaninno, 2014) which is, by its very construction, totally immune to the above problems. Coronal mass ejections are automatically detected on synoptic maps based on their morphological appearance. The automated method is based on adaptive filtering and segmentation, followed by merging with high-level knowledge and resulted in the production of the ARTEMIS I catalog (Boursier et al., 2009). A new generation of high-definition maps later resulted in the present ARTEMIS II catalog (Floyd et al., 2013) which presently covers 21 years (1996–2016 inclusive), except for a short interruption when the SOHO spacecraft lost its pointing from 25 June to 22 October 1998 with normal operations resuming only in March 1999.

This global set of CMEs comprises 37,790 events, approximately twice the number reported by the CDAW catalog, but comparable to the number reported by the SEEDs catalog.[2] The technique used to calculate their mass limits the number to 22,468 events (≈60% of the global population) which defines a sub-set CME_m. We have verified that this selection does not introduce a bias and a visual verification can be performed by inspecting Fig. 1 which displays the temporal evolution of the monthly occurrence rates. It can be seen in the top panel that the rate of ARTEMIS II CMEs (blue curve) and that with a mass estimation (red curve) closely track each other. As a matter of fact, applying a scaling factor of ≈1.6 to the latter curve would bring it in almost perfect agreement with the former curve. Note that, for convenience, our monthly rates are based on a mean month equals to 1/12 of a year. We further distinguish the CMEs coming from the northern and southern hemispheres on the basis of their apparent latitude listed in the ARTEMIS II catalog (CME_N, $CME_{m,N}$ and CME_S, $CME_{m,S}$ respectively), and the occurrence rates of the CME_N and CME_S are displayed in the bottom panel of Fig. 1.

2.2. Description of selected solar proxies

We consider three photospheric indices: sunspot number (SSN), sunspot area (SSA), and total photospheric magnetic flux (TMF). The SSN data come from the WDC-SILSO data center,[3] and the SSA data from the RGO database.[4] The total photospheric magnetic flux, calculated from the Wilcox Solar Observatory photospheric field maps, was kindly made available to us by Y.-M. Wang; detail can be found in Wang and Sheeley (2003). All indices are considered globally and by hemispheres.

[1] http://cdaw.gsfc.nasa.gov/CME_list/.
[2] http://spaceweather.gmu.edu/seeds/.
[3] http://www.sidc.be/silso/datafiles.
[4] http://solarscience.msfc.nasa.gov/greenwch.shtml.