J. Astrophys. Astr. (2000) **21**, 221–227

Cyclical Variability of Prominences, CMEs and Flares

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Abstract. Solar flares, prominences and CMEs are well known manifestations of solar activity. For many years, qualitative studies were made about the cyclical behaviour of such phenomena. Nowadays, more quantitative studies have been undertaken with the aim to understand the solar cycle dependence of such phenomena as well as peculiar behaviour, such as asymmetries and periodicities, occurring within the solar cycle. Here, we plan to review the more recent research concerning all these topics.

Key words. Sun: Activity—prominences—flares—CMEs.

1. Introduction

The long-term evolution of solar activity, on time scales of the solar cycle and beyond, has been studied from different perspectives using a variety of phenomena that have timescales shorter than 11 years. Two of the most studied topics have been the time-latitude distribution of filaments, CMEs and flares and the asymmetry of solar activity. However, sixteen years ago an unexpected short-term periodicity in high-energy flares was discovered by the solar maximum mission satellite and nowadays we have some hypothesis about when and why it occurs. In the following, I would like to review the more recent research done on those topics.

2. Time-latitude distribution of filaments, CMEs and flares

2.1 *Filaments*

Regularities in the time-latitude distribution of the prominences were already described by D'Azambuja's (1948). Later, Waldmeier (1973) pointed out that prominences are distributed in three narrow zones, which show different types of time-latitude behaviour. These zones are: (a) Zone of sunspot type prominences which move along with sunspots originating between 30° and 50°; (b) Zone of long-lived prominences which develop from active centers, migrating towards the equator at a latitude 15° higher than the spot zone; (c) Polar zone at latitudes higher than 45°. Since Secchi (1872) discovered the zone of polar prominences and its poleward motion, this phenomenon has been observed in every cycle and is independent of the intensity of the cycle. The characteristic pattern of the polar zone is a "rush to the poles" and the development of a secondary polar crown on the next neutral line equatorward of the first. This behaviour was well documented by Evershed & Evershed (1917).

Mclntosh (1992) discriminated between high-latitude filaments with "correct" polarity – which means that the polarity of the magnetic field lying poleward of east-west oriented filaments is the one appropriate for that cycle (true polar crown) – from those with "opposite polarity" (emergent polar crown). The kinematic model of the solar cycle tries to explain the polar crown "rush" to the poles as the consequence of diffusion of magnetic fields which accumulated from the dispersion of active regions earlier in the solar cycle. Then, the movement of the polar crown should reflect the numbers and intensities of the active regions while the onset of poleward motion should await some accumulation of flux from numerous active regions. Instead, the motion of the polar crown begins very soon after the sunspot minimum, long before there are active regions. Furthermore, the rate of motion varies little during the rise of the cycle, even though there is a large increase in the number of active regions. Mclntosh (1992) argued that this steady progress must reflect some fundamental subsurface process rather than the surface diffusion of decaying active-region field.

During solar cycle 20, two polar zones appeared in the northern hemisphere (Waldmeier 1973). The first was regular and reached the pole shortly after the sunspot maximum. The second one, irregular and weaker, appeared at lower latitudes only when the regular zone was already disappearing. This anomalous zone also moved towards the pole and disappeared at the beginning of 1971, migrating faster than the regular one. Curiously, the phase shift (1.4 years) between regular polar zones in both hemispheres seems to be related with the phase shift (1 year) between the main zones of activity in both hemispheres. On the other hand, an anomaly which appeared in the migration, towards the equator, of the main zone of sunspots belonging to the northern hemisphere seems to be the cause of the apparition of the second polar zone. This points out the existence of a coupling between the activity in low and high latitudes. Also, in this cycle, a three-fold reversal of the magnetic field occurred in the northern hemisphere as the secondary polar crown followed the first into the polar region (Makarov *et al.* 1983). Benevolenskaya & Makarov (1992) have claimed that triple reversals have happened during all even cycles since cycle 12 and that the mechanism could be the superposition of a high frequency variation on the basic 22-year magnetic cycle. However, there are doubts about the reliability of the records used for this hypothesis. Dermendjiev *et al.* (1994) pointed out that during the ascending phase of the solar cycle 22 a triple structure developed in the southern hemisphere.

2.2 *Coronal mass ejections*

Webb (1991) and Webb & Howard (1994) studied CMEs from 1973 to 1989 concluding that: (1) the frequency of occurrence of CMEs tends to follow the solar activity cycle in both amplitude and phase; (2) considering only long-term averages, all solar activity indices are equally correlated with CME rate.

Cliver *et al.* (1994) obtained Carrington rotation averaged daily rates of CMEs for the period 1979–1989 and performed a correlation plot with the tilt angle of the heliospheric current sheet. A quasi-discontinuity appears in October 1988, when the average daily rate doubled and remained high until the end of solar maximum mission observations in late 1989. Another quasi-discontinuity appeared in 1982 with a decrease in the CME rate. Also, they inferred a similar discontinuity (increase) in the CME rate during 1978.

These discontinuities occur at about the time of the onset of the poleward motion of the true polar crown or at the time of return to the equilibrium position. If the increase in the CME rate in late 1988 is related to the dynamics of the high latitude filaments, then we would expect a change in the latitude distribution of CMEs around the time of the quasi-discontinuity.

Hundhausen (1993) found that the distribution of apparent central latitudes of CMEs for different years shows significant changes in the spread about the equator. For instance, 41° in 1980, 38° in 1989, but only 13° in 1986. The changes in the distribution of CMEs latitudes do not correspond to those for solar features related to small-scale magnetic structures such as sunspots, active regions, or Hα flares. Instead, Hundhausen's (1993) findings support the hypothesis that the latitude distribution of CMEs mimics that of solar filaments. This analysis suggests that there is a close, physical relationship of coronal mass ejections with the disruption of large-scale magnetic structures. Cliver & Webb (1998) made a statistical comparison of high-latitude CMEs with disappearing solar filaments (DSFs) finding that: (1) Beginning with the "rush to the poles", DSFs occur at an increasing rate from the "emerging" polar crown. At maximum, these filaments are the dominant source of high-latitude DSFs. Following polarity reversal, the new true polar crown becomes the source of all high-latitude DSFs; (2) At the last two solar maxima, there were ≈ 4 times as many high-latitude (≥ 60°) CMEs as high latitude (≥ 45°) DSFs. They offer the following plausible reasons for this discrepancy: (a) under-reporting of small DSFs, (b) propagation effects or (c) some combination of both effects.

2.3 *Flares*

A detailed study of Hα flares (1938–1992) and X-ray flares (1982–1992) reveals that flare energy release systematically follows the solar cycle and extends well beyond the main activity zone into higher latitudes (Balasubramanian & Regan 1994). The butterfly diagram for Hα flares is similar to butterfly diagram for sunspots and follows the solar cycle with an extension of the zone of flare activity outside the sunspot activity zone during solar cycles 19, 20 and 21. Also, this diagram already suggests flare asymmetry between hemispheres. The butterfly diagram for X-ray flares shows its concentration in the main activity zone. Concerning the latitude distribution of X-ray flares energies, the majority of X-ray flares extending outside the main activity zone (± 30°) are low intensity C-class flares while only few high intensity X-ray flares occur at latitudes higher than ±40°. On the other hand, the number of flares drastically drops off above a flux of 10^{-3} watts m^{-2} and most of the flare energy appears to be released in the mid-latitudes around ±17°. Then, models that attempt to describe the large scale solar activity should include an explanation of this observed location of maximum energy release.

3. The near 158-day periodicity in high-energy solar flares

The near 158-day periodicity was detected during solar cycle 21 in γ-ray flares (Rieger *et al.* 1984); X-ray flares (Kiplinger *et al.* 1985; Dennis 1985; Kile & Cliver

1991); flares producing interplanetary electrons (Droöge *et al.* 1990); microwave flares (Bogart & Bai 1985) and proton flares (Bai & Cliver 1990). However, during solar cycle 22 there has been no evidence for the presence of this periodicity in any solar flare related indicator. Why do high-energy flares display this periodicity only sporadically?

Energetic solar flares are based on reconnection between emergent magnetic flux and old flux (Forbes 1991; Priest 1990). Then, one could suspect that a periodic behaviour in the occurrence rate of energetic flares could be related to a periodic emergence of magnetic flux, giving place to a periodic variation of the total sunspot area on the Sun's surface (Carbonell & Ballester 1990). To test this hypothesis, we need to prove that the occurrence of the periodicity in high-energy flares coincide with a similar occurrence of periodicity in sunspot areas.

To this end, we applied wavelet analysis to a time series made of daily sunspot areas between 1874 and 1993 in order to study the temporal variation with time scales around 160 days. The analysis reveals the existence of a periodic variation in the emergence of magnetic flux at epochs that coincide with the periodicity found in high-energy solar flares, which suggests a close relationship among them (Oliver, Ballester & Baudin 1998). Recently, a complete re-analysis of solar activity historical archives has been made (Hoyt & Schatten 1998) and the result is a homogeneous database of group sunspot numbers spanning along a 386-year period (1610-1995). This database is compiled from the daily number of observed sunspot groups. We have started our analysis in 1750 and have applied the wavelet technique to a time series made of daily group sunspot numbers between 1750 and 1995, in order to study the temporal variation with time scales around 160 days (Ballester, Oliver & Baudin 1999). After analyzing the whole time series, we find that an episode of the 158-day periodicity occurred around the maximum of solar cycle 2, this being the first time that such a periodicity is detected prior to the twentieth century. After this epoch, a signal appears around the maxima of solar cycles 16 to 21. The detection of the periodicity in this solar activity index provides a strong confirmation for the existence of a periodic emergence of magnetic flux around the maxima of some solar activity cycles. During the twentieth century, the periodicity has appeared simultaneously in sunspot areas and group sunspot numbers, but the periodicity does not manifest with the same strength in both data sets as pointed out by means of Lomb-Scargle periodograms. In order to explain this behaviour, we suggest that the periodic emergence of magnetic flux, which triggers the flares, can occur either by forming new sunspot groups in previously spotless photospheric regions or by creating new sunspots within already formed sunspot groups.

According to the first type of behaviour, new sunspot groups would periodically appear, increasing simultaneously the number of sunspot groups and the total sunspot area, such as could have occurred during solar cycles 16 and 17.

According to the second type of behaviour, the periodic emergence of new magnetic flux gives place to a periodic variation of sunspot areas but not to a variation in the number of sunspot groups. A good example of this case would be solar cycles 20 and 21. Finally, when none of the previous types of periodic emergence takes place, the periodicity in flare occurrence does not appear, as in solar cycle 22. Having this in mind, one can suggest that when the periodicity appears in sunspot as are only, i.e. when the magnetic flux emerges mostly within already formed active regions, a similar periodicity should appear in high-energy solar flares, such as occurred during solar cycle 21. On the other hand, when the periodic emergence of magnetic flux is produced in the form of new and scattered sunspot groups, no periodicity should appear in energetic solar flares.

4. The north – south asymmetry of solar activity

The asymmetry of solar activity between hemispheres has been known for a long time and it has been detected in: (a) Solar flares (Roy 1977; Knoska 1985; Garcia 1990; Joshi 1995; Özgüç & Ataç 1996); (b) Prominences (Waldmeier 1971; Hansen & Hansen 1975; Vizoso & Ballester 1987; Joshi 1995); (c) Magnetic flux (Howard 1974; Tang *et al.* 1984; Rabin *et al.* 1991).

Verma (1992, 1993) has performed the most complete study of N–S asymmetry using different solar activity indicators for solar cycles 8–22. He has suggested that the N–S asymmetry may have a period, or long term trend, around 110 years, however, one has to be careful since we only have data for about 160 years. The presence of this trend has been also studied by Oliver & Ballester (1994) and Özgüç & Ataç (1996).

The most important result is that the shape of the trend indicates that during solar cycle 22 the dominance of solar activity has moved to the southern hemisphere, changing thus the behaviour exhibited during the most recent solar cycles. Also, Verma (1992, 1993) has predicted that the dominance of the southern hemisphere will continue during cycles 23 and 24.

Roy (1977) and Yau (1988) argued that the N–S asymmetry in spots is anti-correlated with solar cycle while Swinson *et al.* (1986) suggested that there is a 22-year periodicity in the N–S asymmetry of spots. However, Garcia (1990) suggested that N–S asymmetry of flares is out of phase with the solar activity cycle and with the N–S asymmetry in spots. All the above are qualitative conclusions based on the shapes of the curves of solar activity and asymmetry versus time while Rank Correlation tests, using sunspot data, suggest anticorrelation although this conclusion has to be taken with care.

The solutions of the linear (Kinematic) dynamo problem have pure dipole or quadrupole symmetry; i.e. toroidal field are antisymmetric or symmetric about the equator. These symmetries can only be broken in the non-linear regime, which lead to the appearance of spatially asymmetric mixed-mode (mixed-parity) solutions (Jennings & Weiss 1991). Brandenburg *et al.* (1989) have studied oscillatory non-linear dynamos finding that one of the features of the solutions is that the symmetry type can vary on a very long time scale compared to the magnetic cycle frequency. Pulkkinen *et al* (1999) have determined the long-term variation (1853–1996) of the latitude of the magnetic equator of the Sun. This latitude is computed as the sum of mean latitude of solar activity in each hemisphere.

The period of this variation is about 8.4 sunspot cycles or 90 years, and the amplitude 1.3 degrees. This variation in latitude can be explained as a mixed-parity mode in which a quadrupolar component is oscillating with this period; however, Stenflo & Vogel (1986) found a small quadrupolar component in the radial field at the solar surface, which oscillates on time scales much shorter than the solar cycle! Thus there is great scope for improvement in the understanding of non-linear dynamos as related to observed N–S asymmetries in occurrence of flares & sunspots.

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