DIPOLE FIELD, SUNSPOT CYCLE AND SOLAR DYNAMO

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Abstract. From the analysis of a series of data concerning phenomena taking place in the high corona, in the interplanetary medium and in the magnetosphere, we came to the conclusion that we have to take into consideration a two-component solar cycle in which, with a 5-6 yr delay, the cycle of the dipole component of the solar magnetic field and the following sunspot cycle are closely correlated. In order to show the new mechanisms to incorporate into a model of a two-component solar cycle, we discuss several other relevant solar data.

1. Introduction

Heinrich Schwabe (1843) discovered the cyclic behaviour of annual sunspot numbers. Later on Wolf, Spoerer, Hale and Nicholson contributed to establish the properties of the sunspot cycle which, by the way, became the "solar cycle".

Babcock pointed out that the cyclic behaviour of the polar fields is out of phase with the sunspot cycle. But this low intensity photospheric field has been supposed to be a "surface field" resulting from the poleward migration of the decaying sunspot field. Therefore, nowadays any phenomenon of solar activity is supposed to depend upon the sunspot field emergence in such a way that the sunspot cycle is the source of any phenomenon of solar activity.

However, from the study of long series of geomagnetic data as well as of shorter series of solar wind data, of coronal holes and of full disk magnetograms, we have shown that the solar cycle is a two-component phenomenon, where the leading phase is the cycle of the dipole component of the solar field (Legrand et al. 1991).

In section 2, we discuss these results and we sketch the new time profile of a two-component solar cycle having a 20-yr duration and occurring each eleventh year.

In section 3, from the analysis of solar data, we suggest new mechanisms to incorporate in a model of a two-component solar cycle in which, with a 5-6 yr delay, dipole and sunspot cyles are closely correlated.

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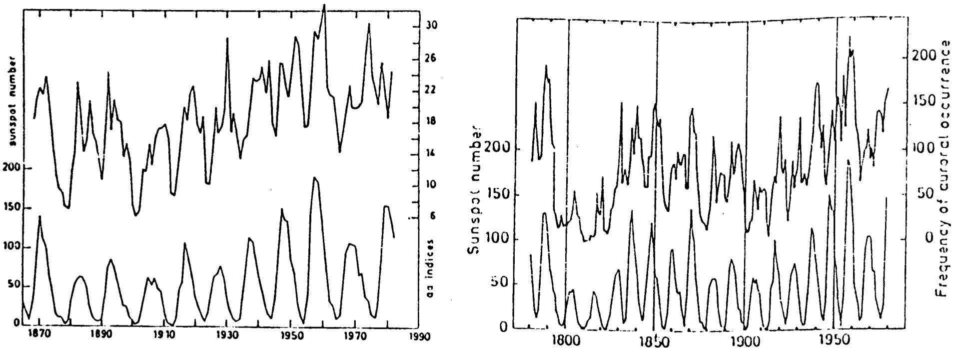

Figure 1. Left: the centenial series (annual averages) of geomagnetic indices aa (top, scale at right) and the relevant series of annual relative sunspot numbers (bottom, scale at left) from 1868 to 1980. Right: the annual frequency of auroral occurrence (top, scale at right) and the relevant series of annual relative sunspot numbers (bottom, scale at left) from 1780 to 1981.

2. The solar cycle in the "outside" Sun

As early as 1966, Ohl discovered that the geomagnetic activity generated by the sunspot activity is superimposed on another component of the geomagnetic activity, of different solar origin, which has an unexpected property: its cyclic behaviour can be used in order to forecast, several years in advance, the sunspot cycle (Ohl 1966, Ohl et al. 1979). These results suggest (1) the occurrence of two separate solar sources of geomagnetic activity and (2) a close correlation between the peak of the solar source of the Ohl's geomagnetic component, and the sunspot maximum number occurring 5-6 yr later.

In order to explain the time profile of geomagnetic activity, we studied the data of the interplanetary medium and of the corona. The interplanetary medium is monitored by spacecraft experiments which carry out in situ measurements, most of them in the ecliptic plane, and by radio scintillation techniques which measure the solar wind velocity all around the sun. We took also in consideration the ground-based observations of full disk solar magnetic fields, which form coronal fields, and of coronal structures from which solar wind escapes. These data form the background in the analysises of the long series of geomagnetic data, beginning 1868, established by Mayaud (Mayaud 1973) and of a series of auroral reports, beginning 1780 (Legrand et al. 1987) (Figure 1).

Our method of geomagnetic data analysis has been previously described (Legrand et al. 1981, Legrand et al. 1985, Simon et al. 1986, Simon et al. 1987). In the series of geomagnetic indices, we found two distincts signatures of interplanetary phenomena:

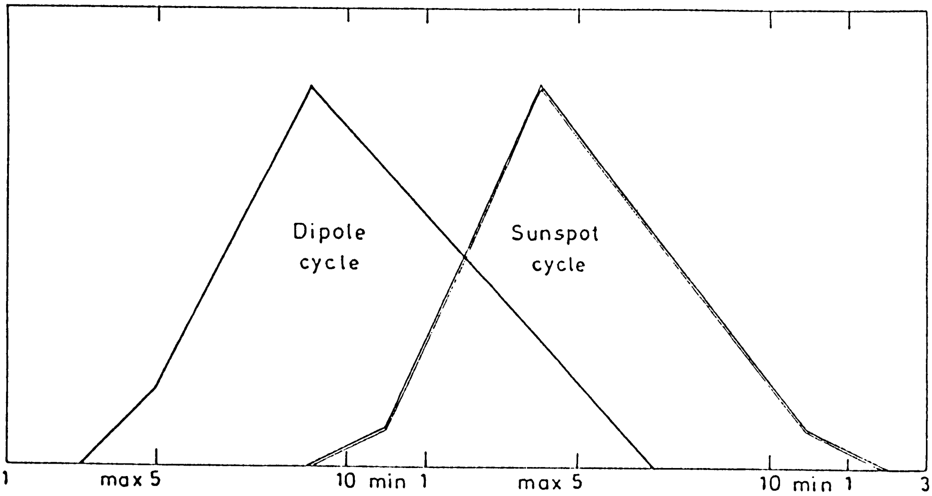

Figure 2. Sketch of the cycles of the dipole component of the solar magnetic field (solid line) and of the sunspot numbers (double solid line) as a function of time in years. max and min stand for sunspot maximum and minimum years respectively. The dipole cycle begins during the main phase of the sunspot cycle and reaches its peak roughly at the beginning of the following sunspot cycle. The two peaks of dipole and sunspot cycles are closely correlated (arbitrary scale).

1. A permanent "wind-component", where the cyclic behaviour is controlled by the cycle of the dipole component of the solar magnetic field.
2. A series of sudden commencement storms generated by shock waves moving in the solar wind. This series of "shock events" is linked to the sunspot activity.

While the geomagnetic data analysis does not pretend to replace the lack of space data, we here extend our study of solar cycles by geomagnetic activity proxy, without any gap, back to 1868, and by auroral activity proxy, back to 1780. The results of this analysis are summarized in (Legrand et al. 1991). We came to three conclusions:

(1) the dipole and the sunspot components of the solar field combine to form a single two-component solar cycle to which we will refer below as the "solar cycle" (Figure 2), (2) during the so-called "solar cycle" the sunspot activity cycle is controlled, with a 5-6 yr delay, by a preceding dipole cycle, and (3) the source of the dipole field is not the poleward migration of the decaying sunspot field but some mechanism taking place beneath the photosphere.

Let us describe more in detail this two-component solar cycle. Figure 3 despicts schematically the time profiles of a series of such solar cycles of low and high activity. For simplicity, all these cycles are supposed to have an 11 year periodicity and all the cyclic components have an identical duration of 14 years independently of their activity level. We distinguish the successive solar cycles by using hatches of opposite inclinations; the dipole and the sunspot components are drawn in broken and solid lines respectively.

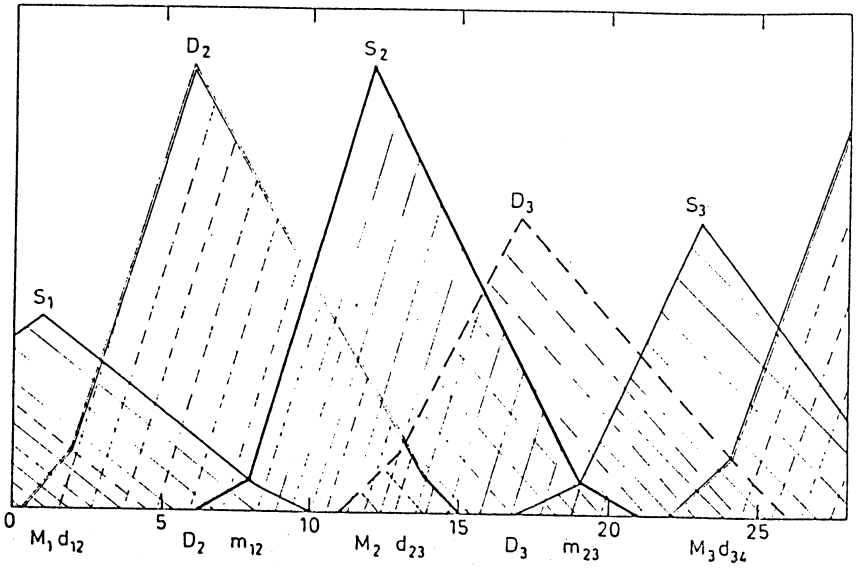

Figure 3. Time profiles of a series of solar cycles of low and high activity (arbitrary scale). All these solar cycles numbered 1, 2, and 3 have an 11-yr periodicity and all the cyclic components an identical duration of 14 years. Opposite inclinations of the hatches are used for the successive solar cycles, the dipole (D) and the sunspot (S) components, drawn in broken and solid lines, respectively, are out of phase but their key parameters are closely correlated. The coronal dipole is built by the emergence into each of the polar caps of unipolar fields of opposite polarities. The series of bipolar sunspot groups take place at mid- and low-latitude. The mechanisms at the origin of each component take place at the same time in separate internal regions of the Sun.

In any cycle, for instance cycle 2, the two components, the dipole field and the sunspot activity, follow cyclic evolutions which are out of phase but their key parameters are closely correlated. The delay between the two components as well as their relationships have been established from our data analysis reported above.

Therefore, in a first phase the dipolar structure of the coronal field is formed: this process concerns the emergence of "unipolar fields" of opposite polarities in the polar caps. Then, with a 5-6 year delay, starts the second phase during which, at mid and low latitudes, are generated a series of bipolar sunspot groups.

However the time profiles of these two processes, which generate different magnetic phenomena in separate regions of the sun, are closely correlated to form a single solar cycle. Thus a solar cycle has two separate but linked peaks of activity: the first one is the maximum intensity of the solar dipole which controls the topology of the coronal field (Legrand et al. 1991) and the second one, 5 to 6 years later, is the sunspot maximum number which, as noted by Waldmeier (Waldmeier 1968), characterizes the time profile of the sunspot cycle.

As a consequence of the every eleventh years occurrence of a two-component solar cycle, the total duration of which is about 20 years, most of the time two separate solar cycles and three of the cyclic components are simultaneously in progress. Consequently there is a permanent overlap of all those cyclic mechanisms which take place at the same time in separate internal regions of the Sun.

The data we used in the above study concern a long series of geomagnetic records but the indices are the more recent ones. The data themselves have been scanned on the years 70s by Mayaud in order to obtain the longest homogeneous series of geomagnetic indices (Mayaud 1973). From the study of all these series of data, we established the properties of the solar cycle going on in the "outside" Sun, from the low corona up to 1 AU. Thus in order to establish some of the new mechanisms and to incorporate them in a model of the solar cycle, we completed our study by considering other categories of solar data.

3. What is going on in the "inside" Sun?

Let us begin by sketching tentatively the framework of the basic movements occurring permanently in the solar interior, those which represent the basic mechanisms and thus the origin of the solar cycle phenomena.

According to the last results of the helioseismology, we have to consider three internal solar regions (Figure 4) (Morrow 1988; Brown et al. 1989):

1. The deepest region, up to a distance of 0.5 solar radius, is the radiative core which rotates rigidly.

2. A transitional layer, from 0.5 to 0.7 solar radius, in which is generated the differential rotation.

3. A convection zone in which that differential rotation does not change with the distance of the Sun's center.

Apparently the mechanism at the origin of the solar cycle should take place exclusively somewhere in the transitional layer. The convection zone just transfers, with more or less reliability, what has been formed in the transitional layer up to the photosphere, to the chomosphere and into the corona.

One can notice at the solar surface the occurrence of a series of polarity zones, separated by neutral lines parallel to the equator. They are moving poleward and each second or third year, a new polarity zone appears at low latitudes and begins its poleward motion (Figure 5). Let us accept temporarily the suggestion of Ribes et al. (1985) that the origin of these polarity zones is a series of azimuthal convective rolls formed at low latitude and moving poleward. That is the second and last piece of our framework.

According to our analysis of a large set of solar data of the last twenty years, three mechanisms contribute together to the solar cycle: the respective sources of the dipole field and of the sunspot groups, and a coupling mechanism which we have only in the photospheric and coronal signatures (Simon et al. 1992).

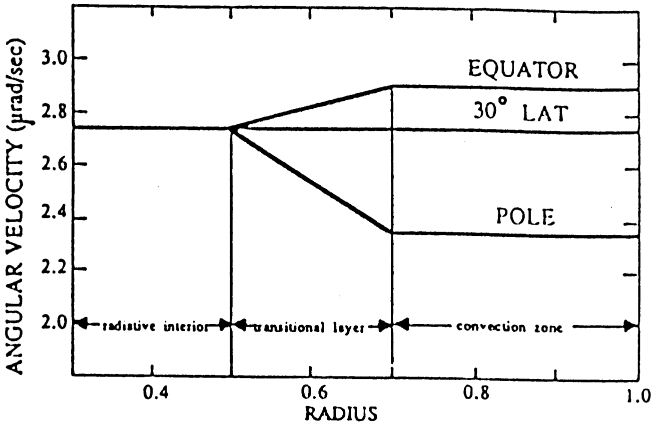

Figure 4. SRF model (surface-like through the convection zone) for internal rotation.

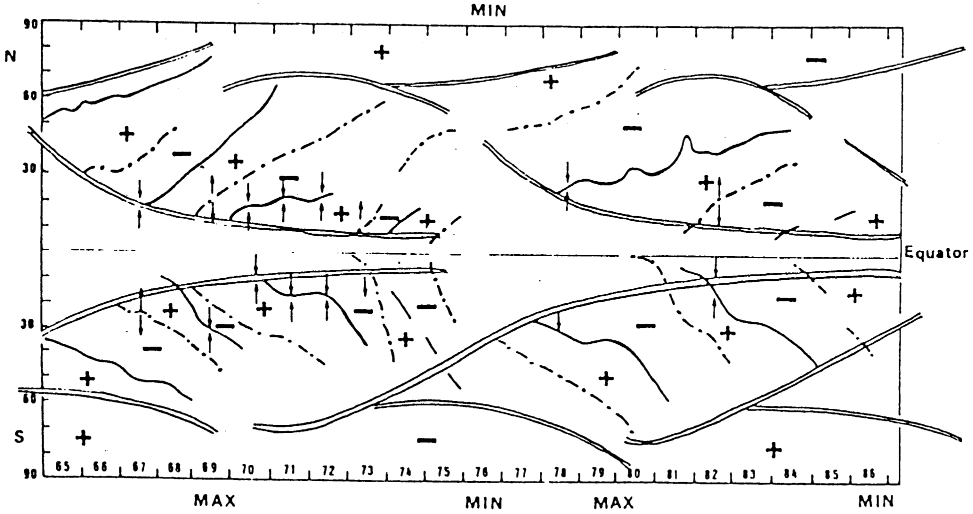

Figure 5. The polarity zones (+ and -) separated by solid and broken lines, appear at very low latitudes, every second or third year and move poleward. They disappear at high latitudes. One can note that they reach the highest latitudes around the sunspot maximum but their poleward motion is stopped at the sunspot minimum. The double line shows the latitudinal variation of the green line coronal activity. At the beginning of the dipole cycle two branches are formed, one moving poleward and the other equatorward. The arrows show the rotation of the azimuthal rolls with the polarity zone formation.

3.1 The sources of the solar dipole

The dipole field is generated by deep-seated sources which rotate rigidly in about 27.3 days. They form a series of low and mid-latitude sources of unipolar field moving poleward and merging, after 1 or 2 years, into a polar source of long lifetime (8-9 years) (Figure 6) (Howard et al. 1981). The dipole reaches its peak at mid time of this interval. At that time, the dipole is not axisymetric but tilted with respect to the Sun's axis around which it rotates in 27 days. At the poles the growth of the dipole field stops temporarily the poleward motion of the azimuthal rolls.

The dipole reversal is generated by the simultaneous occurrence of a new series of sources of opposite polarity at mid-latitude and of the disappearance of the current polar hole. A delay, up to one year, can take place between the two polar field reversals.

3.2 The sources of sunspot groups

At all latitudes the sources of the field of sunspot groups form "pivot points" rotating at 27.3 days (Soru-Escaut et al. 1986; Mouradian et al. 1987; Mouradian et al. 1988). In Carrington coordinates two or three of these sources are at the origin of "active longitudes" which survive through several cycles (Trellis 1971; Trellis 1971).

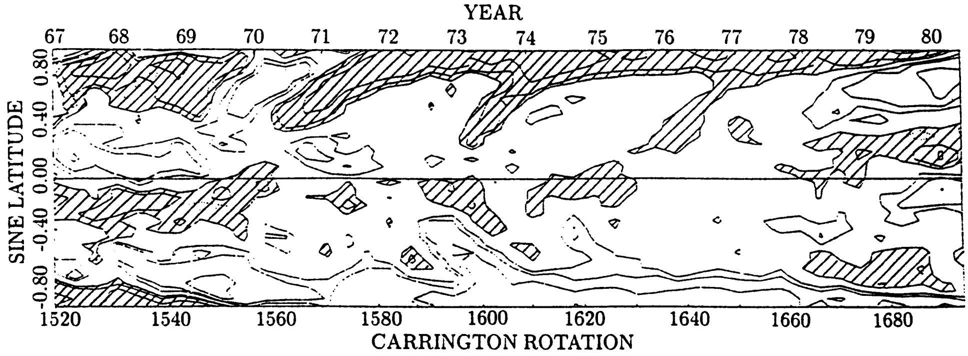

Figure 6. Latitudinal distribution of unipolar solar field. The unipolarity parameter is defined by $(|F+| - |F-|) / (|F+| + |F-|)$*, where* $|F+|$ *and* $|F-|$ *are the absolute values of the positive and negative magnetic fluxes. Contour levels are* $\mp$ *0.1, 0.2, 0.4 and 0.8 G. Hatched contours refer to negative polarity. The solar dipole is generated by the "emergence" at mid-latitude of unipolar fields which move poleward to merge into the long-lived field of the polar coronal holes. The other fields do not show the same latitudinal effect, nor this polar merging.*

The birth of most of the sunspot groups takes place either at the boundary of a plage or close to the inversion line of photospheric field, identified by a filament occurrence (Mouradian et al. 1987).

These inversion lines separate zones of opposite polarities associated with the series of azimuthal rolls of convective origin which, in this case, play a role in the sunspot field emergence. "Pivot points" are the signatures of a local but deep disturbance of the differential rotation by the emergence of the sunspot field.

3.3 Signatures of a coupling mechanism

Two cyclic phenomena, namely the prograde zones (Labonte et al. 1982) and the green line activity (Leroy et al. 1983) (Figure 5), as a matter of fact, are at high latitude closely linked to the growth of the polar field and, at mid and low latitude, to the emergence of sunspot groups (Snodgrass 1987). In absence of any alternate explanation, we suggest that they are the photospheric and low corona signatures of a deep-seated coupling mechanism linking, with the 5-6 yr delay, the dipole cycle to the sunspot cycle.

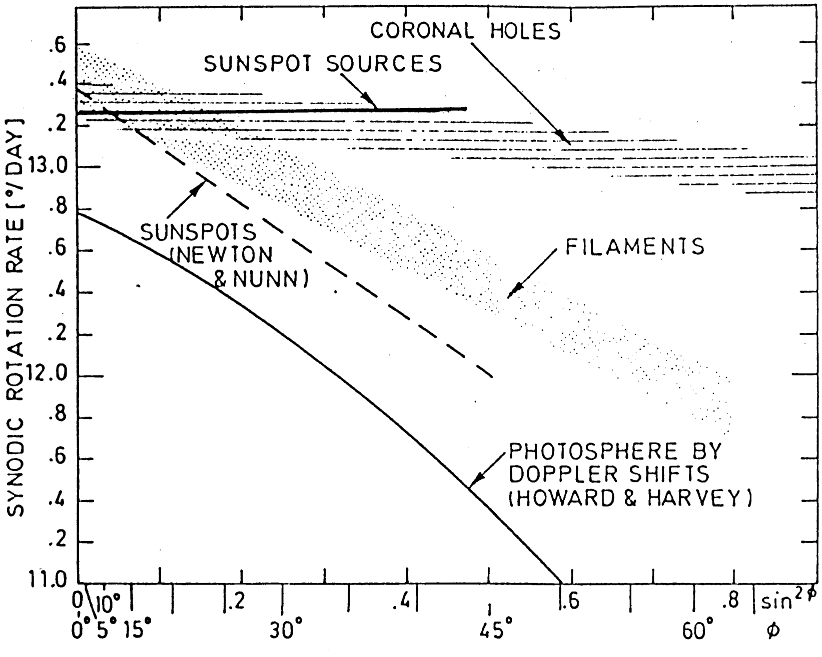

Figure 7. A comparison of the differential rotation laws of the solar activity phenomena under discussion: the sunspot field sources, the coronal holes as tracers of the dipole field emergence, the filaments separating the polarity zones, the sunspots, and the photosphere.

4. Discussion

In the framework described above (section 1) we can use the rotation velocity of the phenomena in order to identify the region in which the relevant mechanisms take place (Figure 7). The two categories of source with a rigid rotation take place in or very close the deepest region (Figure 4), but the dipole sources are at the highest latitudes and their field emerges through a region of low velocity but of the highest differential rotation whereas the sunspot sources are at mid and low latitudes and the field emerges through the region of the weakest differential rotation. The phenomenon linking the two components of the solar cycle take place close to the level of the coupled phenomena, the dipole and sunspot sources. Its equatorward movement disturbs locally the formation of the differential rotation.

5. Conclusion

The main question remains: how reliable are these results which make questionable the currently accepted models of the solar cycle? Let us say a few words of comment about the various items discussed above.

The two-component solar cycle can only be established from long series of cycles of low and high activity and we do not see why the solar machinery will change during the next solar cycles. The suggested process of dipole field building is the natural consequence of the compilation of separate data analysises which are in complete internal agreement. The azimuthal rolls, their contribution to the sunspot cycle has to be specified more explicitely. No physical meaning has been established of the prograde and retrograde zones: it happens that they occur at the right place and time to be a signature of some unknown phenomenon which couples the two components of the solar cycle. The theoriticians will tell us if they need or not a separate coupling mechanism.

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