Astron. Astrophys. 280, 661–665 (1993)

ASTRONOMY
AND
ASTROPHYSICS

On solar activity and the solar cycle. A new analysis of the Butterfly Diagram of sunspots

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Received April 20, accepted May 4, 1993

Abstract. The present paper discusses the duration of solar activity through the active regions from 1981 to 1992. In analyzing the beginning of Cycle 22, we found we had to include in this cycle the reversed-polarity active regions (RPARs) of the decreasing phase of Cycle 21. In fact, RPARs appear as soon as the magnetic polarity of the poles changes, i.e. beginning with the maximum of the previous cycle. Then, analyzing the decrease in Cycle 21, we had to extend this cycle, by including the RPARs of Cycle 22, up to the following maximum. When viewed this way, using data – the active regions – that is homogenous, the whole interpretation of the cycle changes, because the duration becomes 22 years, the change occurs at the same time as the pole polarity, and the source of the magnetic field is located in the equatorial region. In conclusion, we formulate a „Hale-Babcock" law that expresses the magnetic polarity changes of the poles and of the active regions through a complete 22-year cycle.

Key words: solar cycle – solar activity – Butterfly Diagram

1. Introduction

The dynamo theories that have been developed over recent years have been tested to see how well they reproduce the solar activity cycle, whence the need for a better knowledge of this cycle. This was the subject of the reviews of Rabin et al. (1991) and Howard et al. (1991) and of „The Solar Cycle" workshop edited by K. Harvey (1992a).

In a recent article of Mouradian and Soru-Escaut (1991, referred to hereafter as Paper 1), we put forth an empirical model of the Sun's general magnetic field evolution, based on a new analysis of existing observations. The results of this study contradict those of the commonly accepted dynamo models of the solar cycle, which are obtained mainly (a) by a certain interpretation of the Butterfly Diagram of sunspots, and (b) by assuming that the differential rotation is regular. Concerning this latter assumption, it has previously been shown (Deubner and Vasquez 1975; Soru-Escaut et al. 1984, 1986; McIntosh and Wilson 1985; Ambroz 1987; Mouradian et al. 1987; Stenflo 1989) that the rotation of the photosphere is not in conformity with the smoothed, regular law of differential rotation at all points and at all times. This law is established from averages taken over a much greater time span than the lifetimes of the active regions (AR), and therefore overlooks the local conditions that precede the emergence of the ARs.

So in the above-mentioned articles, we began by showing that ARs appear mainly around Pivot Points, which are regions in rigid rotation, where the local rate of rotation is the Carrington rate, regardless of the latitude of the region. This has been confirmed by Bumba and Gesztelyi (1987). Futhermore, we may point out that the majority of ARs are located at latitudes of 15 to 20°, precisely where the differential rotation is zero. This is not a proof in and of itself, but only a confirmation. We may conclude that „classical" differential rotation is only a rough representation of the Sun's rotation, and provides no help in answering the questions raised by the formation of ARs and therefore of the sunspot cycle.

As we had announced in Paper 1, we will be adressing the other aspect of the activity cycle here, i.e. the Butterfly Diagram. In the next paper, we shall study the filament distribution through the solar cycle. Considering that ARs emerge at the border of the opposed magnetic fields, we will first review the AR environment as we had discussed it in Paper 1.

The magnetic field distribution over the entire solar surface shows a weak background field, organized in unipolar magnetic regions (UMRs) or large-scale magnetic fields. This weak magnetic field covers the entire surface of the Sun and the ARs emerge at the UMR borders. Two UMRs of opposite sign are anchored in the north and south poles, and we have labeled these the north and south polar backgrounds. As the solar cycle proceeds, these two UMRs grow alternately in size, extending toward the opposite pole. The north polar background extends beyond the equator during the minimum, partially occupy-

Send offprint requests to: Z. Mouradian ing the southern hemisphere, while the south polar background extends northward beyond the equator during the maximum. At the same time, starting at the equatorial regions, „magnetic islands" of polarities opposite to that of the local background develop in both polar backgrounds. These islands, like the background itself, are subject to the effects of the Sun's rotation and stretch out more or less parallel to the equator. These structures are of the same type as the meridional circulation patterns (rolls) indicated by Ribes, Mein and Mangeney (1985) in that both the rolls and UMRs:

(a) are unipolar regions, magnetically speaking, with a resolution of < 2 arcsec.;
(b) are often bordered by filaments;
(c) are flanked by ARs;
(d) vanish at the cycle minimum.

The difference between UMRs and rolls is that rolls are long-term averages performed on UMRs.

In our observational model of the cycle, we showed that the magnetic "source" of the UMRs is located somewhere near the equator and, as the decreasing phase of the cycle progresses, it migrates with the magnetic background toward the South pole, and toward the North pole during the increasing phase.

In the following, we will be looking at how solar activity varies throughout the cycle according to the Butterfly Diagram of active regions, and we will show that the source of the AR magnetic fields is also near the equator.

2. Active region cycle

The usual definition of the solar cycle is based on two observational facts concerning spot groups: a topological map (the Butterfly Diagram) and a physical law (the magnetic polarity law of the sunspot groups), established by Hale and his fellow workers (see Harvey, 1992 b). This law states that the magnetic polarity of the leading sunspot is maintained throughout the cycle. This provided a homogeneous foundation for the 11-year or even 22-year cycle using the Butterfly Diagram and Hale's law. Then, as new instruments were developed and perfected, Babcock was able to measure the magnetic background field and in doing so, detected the solar dipole. But contrary to all expectations, it was found that the polarity of the poles changed after the activity maximum, right in the middle of the cycle. So Hale's law got twisted into the following: the leading sunspot has the same polarity as the pole of its hemisphere during the increasing phase, including the maximum, and the opposite polarity in the decreasing phase!

To analyze the Butterfly Diagram, we developed one for ARs, and distinguished the ARs by their magnetic polarities. The resulting diagram covers a twelve-year period from 1981 to 1992, including the decreasing phase of Cycle 21 and the increasing phase of Cycle 22, up to just after the maximum.

2.1. *The start of the cycle*

Figure 1 a shows the cycle as it appears in the variation of the monthly mean sunspot numbers (Solar Geophysical Data) and Fig. 1 b represents the Butterfly Diagram of the spotted active regions (Cartes Synoptiques 1981 to 1989). In the second frame, Cycles 21 and 22 are simultaneously present from mid-1986 to mid-1987. To get a better idea how the cycles begin and how they superimpose on each other, we tried to detect the ARs of the very beginning of the cycle from the magnetic field maps of the Kitt Peak National Observatory (Solar Magnetic Field Synoptic Charts in *Solar Geophysical Data*) and those of McIntosh (H-alpha Solar Synoptic Charts in *Solar Geophysical Data*). This convinced us we should include the reversed-polarity active regions (RPAR), occurring after the maximum of Cycle 21, into Cycle 22. These RPARs have magnetic polarities contrary to those of the other ARs in their hemisphere. Up to a certain point, our approach is similar to Harvey's (1992 b). In Fig. 1 d, we show all of the active regions for Cycle 22, as well as the RPARs of the Cycle 21. Let us note that we have plotted in these diagrams only those RPARs that stand out clearly, so we could be sure their polarity was really reversed. Taking them all into account, Howard (1989) find many more RPARs. That is, the emergence of parasitic polarities (Matres et al. 1966; Rust 1968) in the ARs is noticeably due to the RPARs. In reality, the RPARs of Cycle 21 signal the real start of Cycle 22. They begin to emergence at the maximum of Cycle 21, at the time the pole polarity changes. We can offer the following arguments in support of this idea.

(a) The number of RPARs increases regularly from 1981 up to the point where Cycle 22 is usually said to begin, which is about mid-1986. If the RPARs belonged to the current cycle (21 here), they should decrease in number with the cycle, and not increase, as shown in Fig. 2 and Table 1.

(b) According to Hale's polarity law, the RPARs of Cycle 21 are part of Cycle 22. This physical law is more justified that the one that simply decrees that the cycle begins when the ARs appear at the higher latitudes.

(c) According to Howard (1992), the rotation law for RPARs is different from that of the ARs, which might suggest a different behaviour due to the phase of the cycle.

The RPARs were also detected within unspotted ARs. These appear in the same time the latitude patterns as the RPARs. They spread out over the entire width of the AR emergence zone. They confirm the distribution of the spotted RPARs (Table 1).

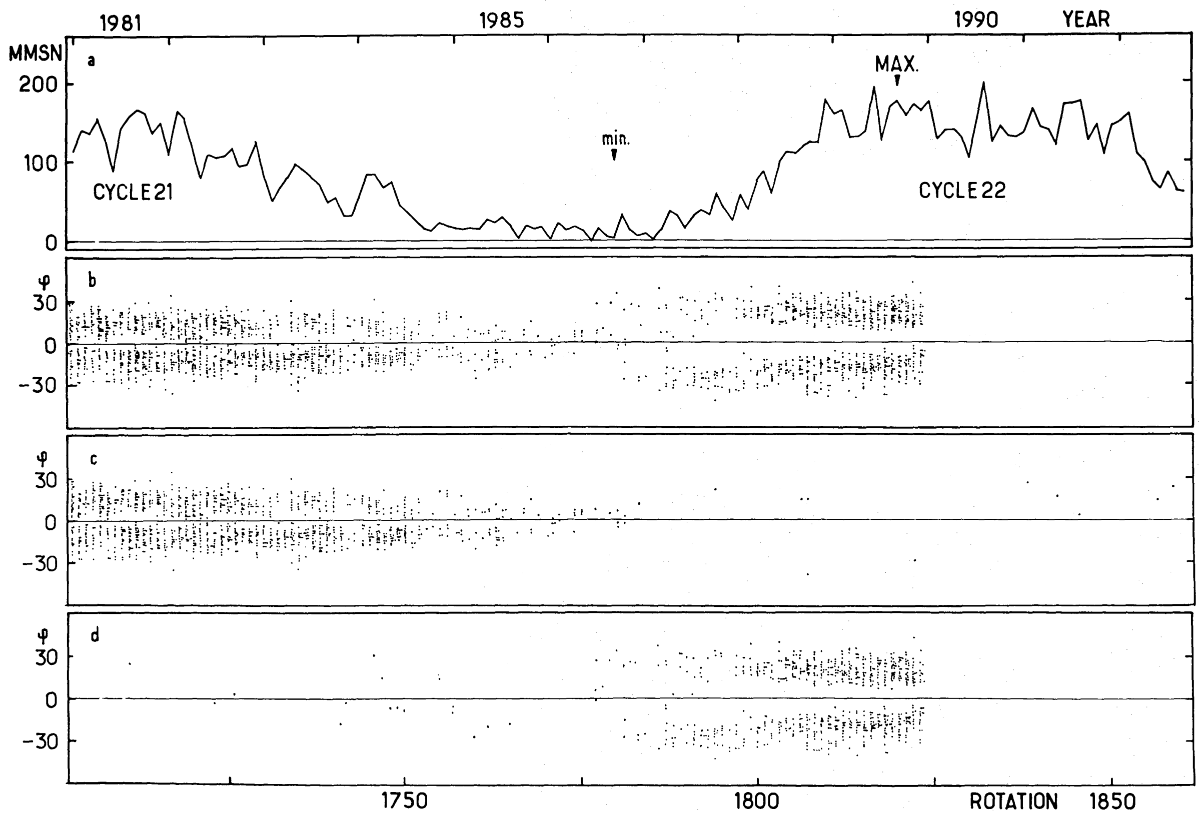

Fig. 1a–d. Solar activity from 1981 to 1992. **a** Variation of the monthly mean sunspot number, **b** Butterfly Diagram of the active regions and of the reversed-polarity active regions, **c** Butterfly Diagram of the decreasing phase of Cycle 21, **d** Butterfly Diagram of the increasing phase of Cycle 22

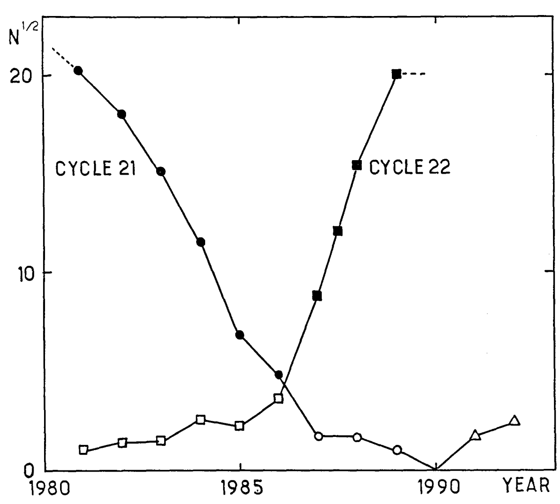

Fig. 2. Number of active regions for Cycles 21 and 22 over the period from 1981 to 1992. The solid symbols represent the ARs and the open ones the RPARs

If we consider that the RPARs belong to the following cycle, we then conclude that the sunspot cycle begins when the poles change polarity and not at the end of the minimum. It should be noted that the pole polarity changes begin at the maximum and is fully completed only during the year that follows, which explains why it is said that the pole polarity changes a year after the maximum. But the change actually begins at the maximum itself, and probably initiates the decrease, which is in turn why the previous activity looks like a maximum. So the beginning of the changes of pole polarity coincides perfectly with the beginning of the sunspot cycle, which begins with the RPARs.

K. Harvey (1992 b) arrived at the same conclusion as we did, as concerns the beginning of the cycle, but for her the cycle lasts 14 to 15 years because she considers only the higher-latitude RPARs. This does go along with the postulate that the cycle must begin at high latitudes, but this postulate has no physical foundation, at least for the time being.

The final list of ARs (Cartes Synoptiques) has not yet appeared for Cycle 22, so we ended the Butterfly Diagram of Fig. 1 at the end of 1989.

2.2. *The end of the cycle*

We also wanted to pick out the last AR of Cycle 21. We see in Fig. 1 b that the ARs of the two cycles are mixed in 1986, and that there is not distinct separation between the old cycle at low latitude and the new one at high latitude. That is, the last ARs in Cycle 21 extend in the form of RPARs up

Table 1. Total number of ARs and RPARs with and without spots

Cycle \ Year	1981	1982	1983	1984	1985	1986	1987	1988	1989	1990	1991	1992
21	823	761	527	346	146	131	≧ 7	≧5	≧3	0	0	0
22	≧1	≧4	≧4	≧10	≧11	≧30	≧86	600	832	?	?	?
23	0	0	0	0	0	0	0	0	0	≧1	≧5	≧6[a]

[a] Figure found by doubling the number of RPARs for the first six months of 1992

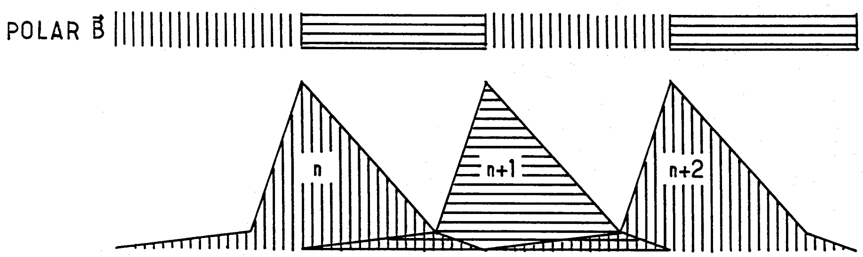

Fig. 3. Schematic of three successive cycles according to the „Hale-Babcock“ law (see body of text) for the variation of the magnetic cycle of the poles (top) and of the active regions (bottom)

to and beyond the maximum of Cycle 22 (Fig. 1c). It is probable that the maximum is past here, and that these are the first manifestation of the future Cycle 23.

We can see in Fig. 1 that it is difficult to distinguish the ARs from the RPARs in 1986 because of the blending of the cycles, and even the conventional distinction by latitude does not work very well. Let us note that at the time of this writing, the RPARs of Cycle 23 have already begun to appear. Table I gives the numbers of spotted and unspotted ARs assigned to Cycles 21, 22 and 23. The ">" sign indicates that the figure mentioned is a lower limit, because of the severity of our selection. Figure 2 gives the variation in the number of ARs and RPARs over the period studied.

2.3. *North-south asymmetry*

Like others before us (Swinson et al. 1986; Carbonell et al. 1993) we have observed that ARs exhibit north-south asymmetry. In the increasing phase of the cycle, there are more ARs in the northern hemisphere than in the southern. The same asymmetry is also visible on the RPARs of Fig. 1c. During the period from 1990 to 1992, the northern hemisphere contained more RPARs, probably belonging to Cycle 23, which precedes the north-south asymmetry of the ARs of this cycle. We also note that, toward the end of Cycle 21 in 1988–1989, the RPARs appeared preferentially in the southern hemisphere. The north-south asymmetry was mentioned by us (Paper 1) in relation with the UMR distribution on the solar surface.

3. Conclusion

Our results support those of Wilson et al. (1988), Simon and Legrand (1992) and Harvey (1992b) in favoring the extension of the cycle duration but, contrary to these investigations, the duration of the cycle for us is 22 years. We locate the origin of strong magnetic fields in the equatorial regions between $+40$ to $-40°$. For some authors, the cycle begins near the poles and trends equatorward with time. This is what is found when structures of different types are added, like polar faculae, the coronal green line, and spots. Note that the strength of the magnetic fields of sunspots compared with other structures is in a ratio of about ten or hundred to one, and so there seems to be no easy way to combine all of these features. On the other hand, our results are based on homogeneous data because they refer only to active regions. Let us point out that two other types of observations (also homogeneous) contain poleward motions from the equator during the cycle: azimuthal rolls (Ribes, Mein and Mangeney, 1985) and of the filaments (Makarov and Sivaraman, 1989).

These last two findings, taken in combination with our results, lead us to conclude that the source of the magnetic field is located in the equatorial regions, which is in perfect agreement with the observational model of the cycle we established before (Paper 1).

On the basis of the above results, we may say that the activity cycle contains two magnetic flux waves at all times, each with a 22-year period, and in phase opposition.

Under reserve of future verification, we may conclude by saying that the cycle duration is 22 years and that two cycles are present at any given time: the older one in decreasing phase and the more recent one in increasing phase. In other words, a cycle $n+1$ that begins during the decreasing phase of cycle n reaches its maximum development when the pole polarity changes, and then dies out in the increasing phase of cycle $n+2$ (Fig. 3). So we can formulate the magnetic polarity law for each cycle in the form of a combined "*Hale-Babcock*" *law* that says:

throughout the entire 22-year duration of the cycle, the leading spots retain their polarity, which is that of the pole of the hemisphere in which it is located in the cycle starting phase. Every eleven years a new cycle begins, triggering the decline of the old cycle. Figure 3 roughly diagrams this principle.

Acknowledgements. The authors are indebted to Prof. J. C. Pecker and to Dr. A. Mangeney for helpful discussions.

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