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After a century with Maunder's butterfly diagram

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Abstract. The evolution of the sunspot zone in cycle 20 is described. To reduce the noise which covers any structure in the butterfly diagram, the spot zone boundaries and its geometrical "center of mass" (c.m.) have been smoothed by means of a running window. This operation has eliminated any short period fluctuation, and given visibility to long duration phenomena. One of such phenomena is the fact that the equatorward drift of the spot zone c.m. results from the alternation of five or six prograde (namely, equatorward) segments, with other stationary or poleward segments. The duration of the stationary/retrograde phases amounts to $\approx$ 38% of the total duration of the cycle. In prograde phases, the drift rate is so high that the cycle duration would be half the actual one, if there were no stationary/retrograde phases. Moreover, even the smoothed spotted area markedly oscillates.Links between these phenemena and the tachocline rotation rate oscillations are proposed.

Key words. Sun: butterfly diagram – solar cycle – tachocline

1. Introduction

A century ago, the latitude-time diagram of sunspot distribution – the "butterfly diagram" – appeared for the first time in a famous paper by Maunder (1904). Afterwards, the same author drew a diagram representing (see Figure 3 in Maunder; 1922) "*the changing distance from the solar equator of the center of gravity of the sunspot zones*" *versus* time in the interval 1855-1912, and described it by saying: "*each cycle begins with an activity in high latitudes; each cycle ends with the last remnants of activity transferred to a low one.* Broadly speaking *we may say that the approach toward the equator is continuous from the beginning of the cycle to its end.*" Maunder did not mention the fact that – as his drawing reveals – the center of gravity of the spot zone interrupts its equatorward drift for some time *in all the cycles he studied*.

It would be hard to claim that our knowledge of the subject has increased in proportion to the long time elapsed since those works. On the contrary, Maunder's cautious expressions have been frequently misunderstood, as if no exception had been ever observed, rather than suggest the need for a deeper insight. For example, Waldmeier (1966) wrote that "*from the beginning to the end of the cycle the mean distance of the spots from the equator is decreasing continuously*".

It may surprize that the photospheric activity, schematically depicted by means of sentences as the aforementioned one, has been –

Send offprint requests to: M. Ternullo throughout a century – an unquestioned starting point for the enormous amount of theoretical work performed to understand the nature of the solar activity, in spite of the awareness, clearly expressed by Kopecký (1966) – that *"the solution of the fine structure of the butterfly diagram is now the most important problem in the study of the periodicity of the solar activity. . . .* [The solution] *will give the reasonable basis for establishing the hydromagnetical models of the periodicities of sunspots"*.

2. Working out data

The data used for the present work have been obtained from the observations carried out at INAF – Osservatorio Astrofisico di Catania. On the basis of these data, I determined, for each observation day and for the northern and southern hemipheres separately, the total spotted area A, the extreme (equatorward and poleward) latitudes (λ_e and λ_p, respectively) where spots were registered, and the latitude of the spot zone center of mass (c.m.):

$$\lambda_{c.m.} = \frac{\Sigma_i \lambda_i A_i}{\Sigma_i A_i}$$

λ_i and A_i being the latitude and the area of the i-th group registered on the day and in the hemisphere under examination.

Maunder's butterfly diagram does not display fine structure. Indeed, the complexity (and, accordingly, the unpredictability) of the physical processes which drive the magnetic flux tube eruption makes spots scatter at broad intervals of latitudes. Since all groups are given equal weight, regardless of their extension, the diagram is dominated by small groups, which scatter on wider latitude ranges than larger groups. Provided that the latter were arranged in a finely structured way, the former, which are more ubiquitous and fill more uniformly the diagram, would mask such structure, acting as a noise.

To reduce the noise, I have smoothed the time series of A, λ_e, λ_p and $\lambda_{c.m.}$ by means of a running window; precisely, a triangular, symmetric, 365-day large running window. That means that any datum registered on day t – let's say, *e.g.*, $\lambda(t)$ – has been replaced by the mean resulting from 182 data preceding, and as many following it. Each of the input data is given a weight which is maximal for the central datum and linearly decreases toward zero, with the increasing temporal distance from the day t. The effect is that, if a signal with period $T < 365$ days is present in the input data, replacing each datum with average values computed from time intervals longer than T amounts to the suppression of that signal; such a suppression makes clearer any signal with period longer than the window width.

3. Results and discussion

Figure 1 shows, for cycle 20, the smoothed time series of A, λ_e, λ_p and $\lambda_{c.m.}$ plotted *vs.* time. A glance reveals that neither the boundaries of the spot zone, nor the c.m. migrate monotonically toward the equator. On the contrary, the equatorward drift of these traces is frequently interrupted by stationary phases, and even by pronounced *backward* (poleward) shift phases.

This complex scenario is *the butterfly diagram fine structure*. While referring the reader to Ternullo (2007) for a detailed exposition of the results concerned with the evolution of the spot zone in cycles 20 through 22, we discuss some remarkable points.

First of all, we should approach the question whether the fine structure is either a real phenomenon, deserving attention from the theoreticians, or a meaningless consequence of the turbulent, not fully predictable phenomena involved in the magnetic flux eruption. If the second hypothesis were correct, the alternating prograde-retrograde drift of the spot zone would be but a statistical fluctuation overimposed to the continuous equatorward migration. I believe that the fine structure deserves attention because it has been revealed by a smoothing procedure which is effective in cancelling the noise, and in giving visibility to oscillations with a period longer than one year – that is ≈ 10% of the cycle total duration.

Accordingly, any poleward drift of spot zone, which remains visible in Figure 1 in spite of the smoothing algorithm by which the Figure has been produced, cannot be due

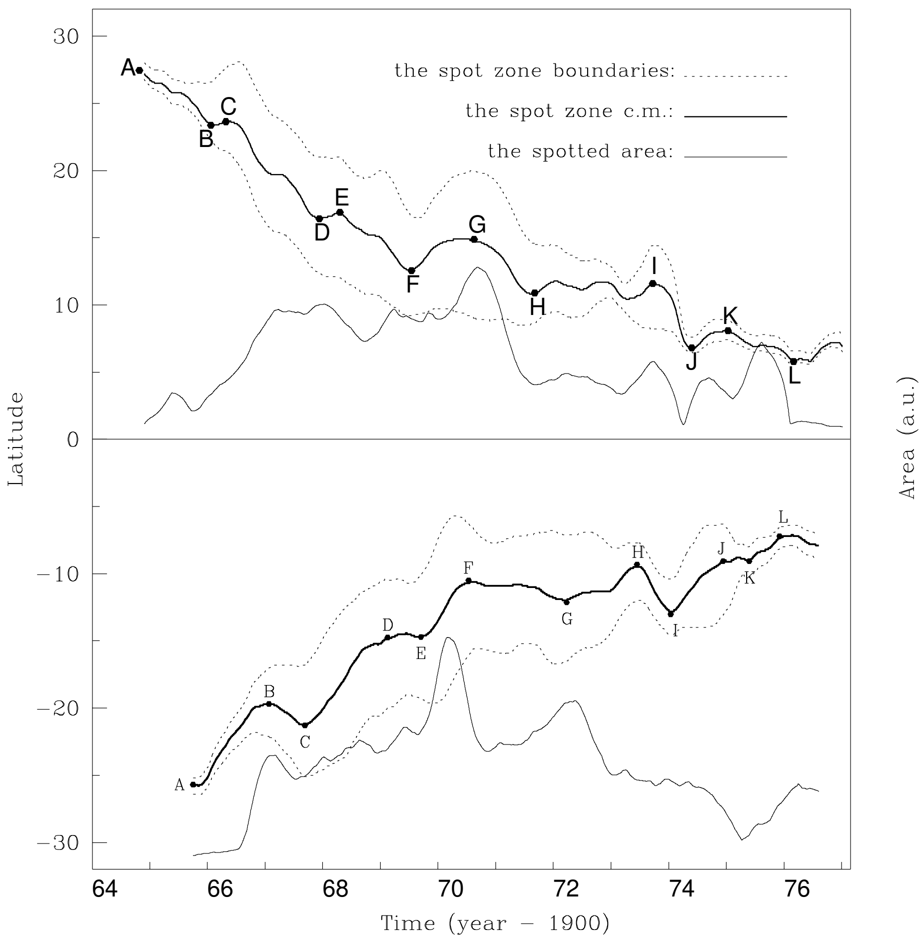

Fig. 1. Spot zone and spotted area in cycle 20. The area is plotted together with the spot zone to allow for the search of correlation between the pulses of spot activity and the changing direction of the c.m. drift.

to some short duration displacement of the spot zone, as a statistical fluctuation would be. This conclusion is strengthened by the fact that poleward drifts occur several times in both hemispheres.

A quantitative description of this complex pattern should begin by giving the location (time and latitude) of the points lying at the separation between prograde and stationary/retrograde segments of the c.m. trace. In Figure 1, the most significant of these points are marked by capital letters. The c.m. traces result from the alternation of some prograde (namely, equatorward) segments ($A-B$, $C-D$, $E-F$, $G-H$, $I-J$ and $K-L$), with stationary or retrograde ones ($B-C$, $D-E$, $F-G$, $H-I$ and $J-K$). If we assume that the time associated with any point is affected by the indetermination $\sigma_t = 25$ days, the time interval between two events is affected by $\sigma_{\Delta t} = 25\sqrt{2}$ days and the sum of n intervals by $\sigma_{\Sigma_{\Delta t}} = 25\sqrt{2n}$ days.

Taking the data pertaining to both hemispheres into consideration, the total duration of the retrograde or stationary phases is 3050 ± 110 days (five of them occur in the northern and as many in the southern hemisphere); this figure represents ≈ 38% of the duration of cycle 20, resulting from summing ≈ 4150 and ≈ 3750 days for the northern and southern hemispheres, respectively. Even if one suspected that the duration of any retrograde/stationary phase was over-estimated by 100 days (the semicycle duration remaining unchanged), the fraction of cycle elapsed in non-prograde phases would reduce to ≈ 26%. Even on such pessimistic – and unrealistic – assumption, the phenomenon would be absolutely reliable.

During genuine prograde phases, the c.m. drifts at an average rate of $4.42 \pm 0.46^{o}\mathrm{y}^{-1}$. This figure is so high that the cycle duration would be half the actual one, if some other phenomena did not occur. We are faced, therefore, with a paradox: even the prograde phases are "anomalous" because of their unexpectedly high rate. Indeed, the prograde phases require the retrograde ones, and vice versa, thus the cycle has its expected duration. In other words, the c.m. retrograde phases should not be regarded as accidental, but as essential features of the 11-year cycle, since the cycle has its duration because prograde, high speed phases alternate with retrograde ones, producing the c.m. oscillating drift.

Figure 1 shows that the smoothed spotted area (shortly, the area) undergoes marked oscillations, too. Such oscillating behavior of the area has already been described by Ternullo (1997). C.m. drift oscillations and area oscillations are out-of-phase. Indeed, in the s.h. we see, at the beginning of the cycle, the area rapidly increasing during the *AB* equatorward drift of the c.m., and decreasing in the following *BC* poleward drift. On the other hand, the next maximal value of the area occurs at the event *G* epoch, that is while the c.m. is in a point of maximal poleward regression. Moreover, during the first half of the *EF* equatorward drift, the area increases until a maximal value, and afterwards decreases whilst the c.m. is still drifting ahead.

It seems that, after the beginning phases, the spot zone gains a high degree of complexity, being formed by several centres of activity, which activate and die at different epochs. If, at the epoch of its activation, one of such centres lies on the poleward side of the pre-existing spot zone, that will make the c.m. rapidly drift poleward. The contrary happens if the new centre of activity lies on the equatorward side of the c.m. In both cases we see that the area increases.

The links between such oscillations and other periodic phenomena should be explored. In particular, the 1.3 y period rotation-rate oscillation which has been detected in the tachocline at $0.72R$ (Howe *et al.*, 2001), could be involved in the c.m. drift rate oscillation and in spotted area oscillations. Indeed, since the tachocline plays a crucial role for the solar dynamo and, accordingly, for its photospheric manifestations, it seems reasonable that the tachocline rotation-rate oscillations may affect both the photospheric activity and the spot zone drift rate.

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