Unveiling the butterfly diagram structure

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Abstract. A Butterfly Diagram showing the spotted area distribution is presented. The diagram reveals that most of the spotted area is concentrated in few, small portions ("knots") of the butterfly wings. A knot may appear at either lower or higher latitudes than previous ones, in a seemingly random way; accordingly, the spot mean latitude abruptly drifts equatorward or even poleward at any knot activation, in spite of any smoothing procedure. The description, assuming that spots scatter around the "spot mean latitude" steadily drifting equatorward, is questioned. In a relevant number of cases, knots appear to be arranged in two roughly parallel, oblique streams, the "spot mean latitude" being located in the underspotted band lying between these streams.

Keywords. Sun: activity, Sun: magnetic fields, Sun: sunspots

Recent works have shown that the trace of the spot zone centroid in the Butterfly Diagram (BD) results – in any hemisphere – from the quasi-biennial alternation of high-speed prograde phases with stationary or even retrograde phases, the average total duration of the latter phases amounting to $\approx 35\%$ of the cycle total duration (Ternullo 2007a,b,c). Moreover, Ternullo (2008, 2010a, 2010b) has shown that most of the spotted area is concentrated in small portions ("*knots*") of the BD, giving it a *"leopard skin"* aspect. An attempt to describe the order governing the knot seemingly random distribution is made with the present work. The data set compiled at the Royal Greenwich Observatory, integrated with data compiled by the US Air Force Solar Observing Optical Network and the NOAA has been used (Hathaway *et al.* 2003).

For each of the 1696 Carrington rotations (from the 330th to the 2025th) and for each of the 84 $1°-$wide latitude strips in the interval $-42, +42°$, the spotted area average values have been computed. The resulting figures are the elements of an 84×1696 array. This array has been smoothed by a triangular running window covering 5 Carrington rotations and visualized by means of level curves. A portion of the resulting diagram is shown in Figure 1 (cycles 15-17). Here, the aforementioned *"leopard skin"* aspect is apparent. Knots are the signature of *sunspot nests* (Castenmiller et al. 1986). A knot may appear at a latitude either higher or lower than that of previous ones. Figure 1 suggests that in some cycles (e.g., 15, 16 and 17 [s.h.]), knots are arranged into two oblique, discontinuous, roughly parallel streams, between which an underspotted band may be recognized. The existence of such a pattern may be proved by decomposing any wing into a set of oblique, 1°-wide "elementary bands", whose slope is allowed to vary at small steps, and thereinafter visualizing the sums of the array elements falling inside each elementary band by a histogram (a histogram for any slope). If an underspotted band actually crosses a wing with the unknown slope $\sigma° \, \mathrm{yr}^{-1}$ (measured in degrees per year units), we expect to see a depression in the central portion of the histogram plotted for such a slope value.

This approach has quantitatively confirmed that depletion channels actually exist even in cases where – due to the knot pattern complexity – it was not trivial to single out
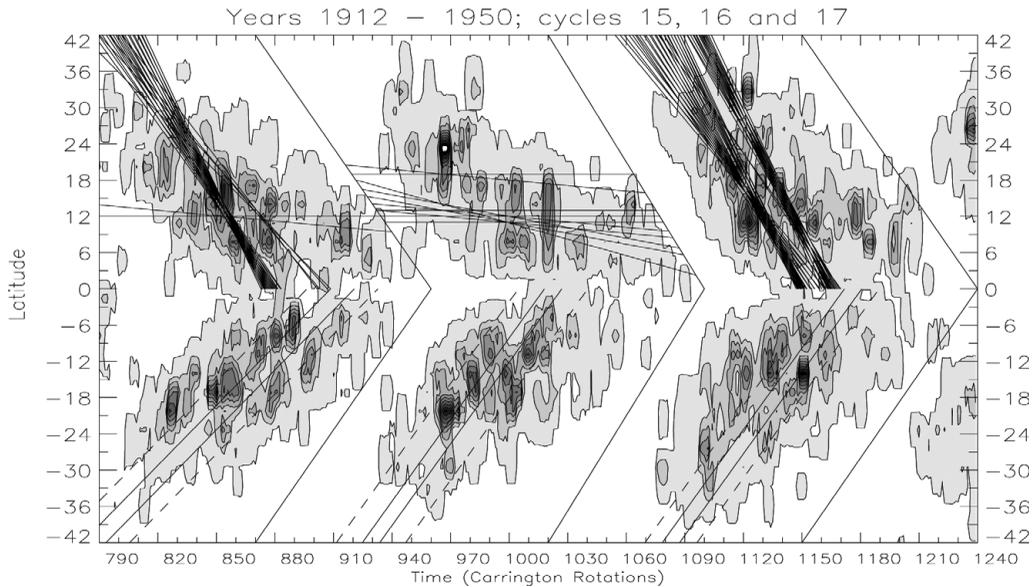
Figure 1. Butterfly Diagram for Carrington rotations 790–1300 (years 1912–1950). The sunspot area distribution is represented by means of 10 level curves, dividing the range of spotted area values into equal intervals. The levels of grey qualitatively correspond to the spotted area density. The Butterfly Diagram appears as a cluster of small, highly concentrated spotted area aggregations (= *knots*): this is the *leopard skin* pattern. In any butterfly wing, it is possible to single out in many different ways a triplet of channels such that the spotted area density in the central channel (the *"depletion channel"*) is significantly lower (at a level of significance not lower than $7\,\sigma$) than in both adjacent comparison channels. As regards the southern hemisphere (s.h.), only one triplet of channels – namely, the one characterized by the maximal level of significance – has been depicted for any wing, As regards the n.h., any triplet of channels fulfilling the same statistical requirements is schematically represented by the line passing through its center.

them at a glance. Moreover, their slopes vary in a restricted range (≈ 4 to $8°\,\mathrm{y}^{-1}$). This finding enables us to conclude that any typical spot cycle actually splits into two activity waves, in any hemisphere; the cycle begins with the activation of the first wave, at a latitude usually not larger than $24 \approx 30°$; it generates the knots lying by the butterfly wing equatorward boundary; the second wave starts a couple of years after the first, at a latitude higher than the first one. Accordingly, spotgroups belonging to different waves lie in belts ≈ 6 through $10°$ apart. The depletion channel marks the separation between these two waves of activity; its slope amounts to the equatorward drift rate of each wave. The sequence of activations and extinctions of knots belonging to either stream accounts for the zigzag displacements of the spot zone noticed by Norton & Gilman (2004) and extensively described by Ternullo (1997, 2001, 2007a,b,c): indeed, the activation of the second wave mimics the first poleward drift of the spot zone centroid; afterwards, other retrograde phases occur because of the extinction of a low latitude knot followed by the activation of a high latitude one.
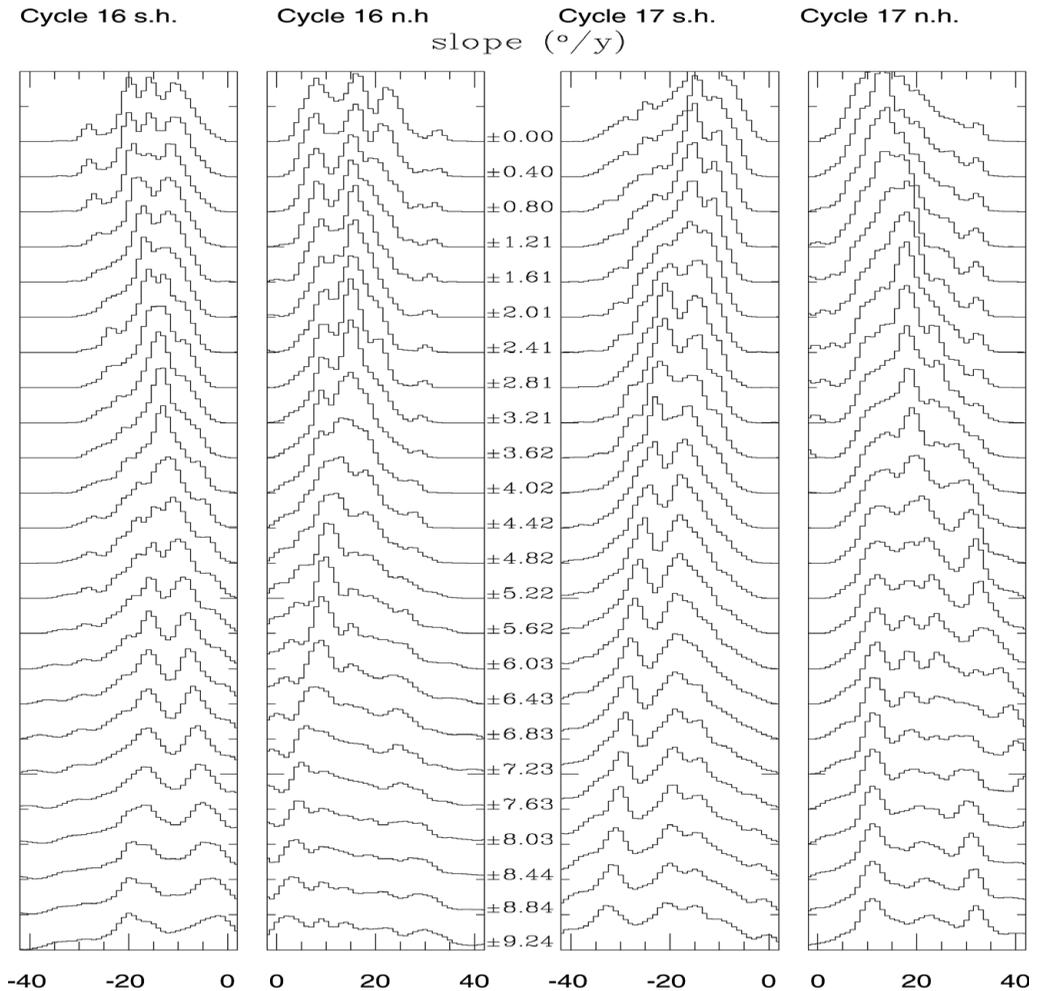
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Figure 2. Histograms showing the spotted area distribution in sets of parallel, oblique, 1°-wide elementary bands scanning the Butterfly Diagram (cycles 16 and 17). The slope scans the range $[0, \pm 9.24°\mathrm{yr}^{-1}]$ (slopes are positive for the s.h. and negative for the n.h.). Each band is assigned to the latitude it crosses at the maximum activity epoch. By sequentially examining histograms related to a given semicycle, it is easy to find that a small dip becomes a sharper and sharper depression until a special slope value is attained; for further slopes, the inverse process occurs.

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