

The Butterfly Diagram Internal Structure

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Abstract. A time-latitude diagram, where the spotgroup area is taken into account, is presented for cycles 12 through 23. The results show that the spotted area is concentrated in few, small portions (“*knots*”) of the Butterfly Diagram (BD). *The BD may be described as a cluster of knots.* Knots are distributed in the butterfly wings in a seemingly randomly way. A knot may appear at either lower or higher latitudes than previous ones, in spite of the prevalent tendency to appear at lower and lower latitudes. Accordingly, the spotted area centroid, far from continuously drifting equatorward, drifts poleward or remains stationary in any hemisphere for significant fractions ($\approx 1/3$) of the cycle total duration. In a relevant number of semicycles, knots seem to form two roughly parallel, oblique “chains”, separated by an underspotted band. This picture suggests that two (or more) “activity streams” approach the equator at a rate higher than the spot zone as a whole.

1. Introduction

It is widely accepted that the Butterfly Diagram (BD) represents the scattering of spots around a mean latitude *steadily* drifting equatorward. Nevertheless, this description of the spot zone structure is hardly reconcilable with others, given by many authors. Bell [3] described the spots as appearing in distinct *non shifting* belts; Antalova and Gnevyshev [1] stated that “*there is no steady equatorward progression of a single maximum of activity*”, Gnevyshev [9; 10] recognized that the cycles from 12 to 19 show two activity peaks, a couple of years distant from each other. This important feature has been confirmed by further works [2; 14; 16] involving various indices of the solar activity. Ternullo [18] described the activation of new long-living activity centers, on the poleward side of the pre-existing spot zone, mimicing the inversion of the familiar equatorward drift of the spot zone centroid [19; 20]; Norton and Gilman [15] observed that “*the sunspot belt migration toward the equator does not proceed as smoothly as is commonly perceived*”. Similar conclusions have been reached by Cho and Chang [7]. The examination of the cycles 20 to 23 [21] showed that, in any hemisphere, the trace of the spot zone centroid results from the quasi-biennial alternation of high-speed prograde phases with stationary or even retrograde phases; the average duration of the latter phases amounts to $\approx 35\%$ of the cycle total duration. A detailed picture of the BD internal structure has shown [24; 25] the striking lack of homogeneity of the spotted area distribution inside the butterfly wings: indeed, most of the spotted area is concentrated in some small portions (“*knots*”) of the BD, so as to give it a “*leopard skin*” aspect. The present work extends the study of the BD structure and evolution to the whole set of cycles 12 to 23. The Royal Greenwich Observatory data – integrated with data from the US Air Force and the US National Oceanic and Atmospheric Administration from 1976 onward – have been used. These data are available at the site <http://solarscience.msfc.nasa.gov/greenwch.shtml>.



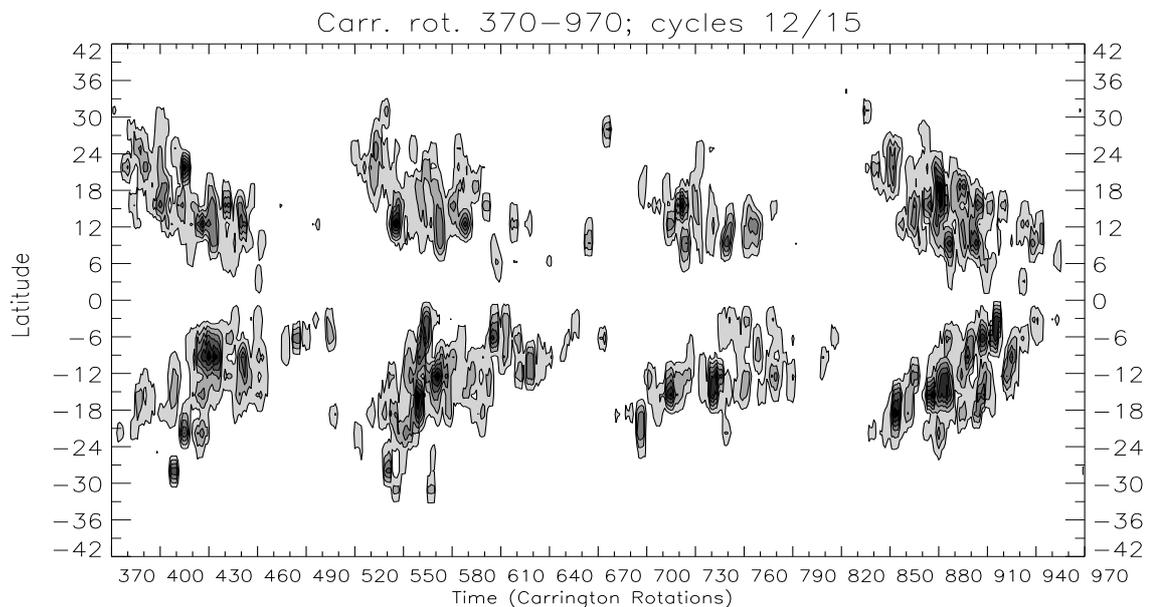


Figure 1. Butterfly Diagram for Carrington rotations 370-970 (years 1881–1926)

2. Results

For each of the 1741 Carrington rotations (CR's) from the 370th (June 1881) to the 2110th (May 2011) and for each of the 84 1° -wide latitude strips in the interval $-42, +42^\circ$, the average value of daily spotted area has been determined. The resulting figures are the elements of an 84×1741 array, which is the quantitative counterpart of the diagram drawn by Maunder. This array has been smoothed by a running window covering 5 CR's, to suppress short period events and give visibility to features lasting longer than 5 CR's, as *complexes of activity* [4; 8] or *sunspot nests* [5]. The resulting smoothed array is visualized in Figures 1 to 3 by means of level curves, for which the term “*isospotted*” is suggested. For any semicycle (that is, for any “wing” of the BD), the first (the most external) isospotted excludes all the array elements spotted at a level lower than 10% of the spotted area maximal value registered in that wing. Inner isospotted are plotted for levels 20, 30, ... 90% of the maximal value. The area of the BD portions lying between the two most external lines typically amounts to $\approx 70\%$ of the wing area, but host only $\approx 20\%$ of the total spotted area. On the other hand, the 3rd level lines circumscribe less than $\approx 15\%$ of the wing area but contain $\approx 50\%$ of the total spotted area. These data support the description of the BD as a cluster of small, highly concentrated spot aggregations (*knots*).

A first-approach description of the spot zone evolution may be given by involving the most external level curves only. Their examination reveals that the first spots of any cycle appear at latitudes usually not higher than $25 \approx 30^\circ$. Afterward, the spot zone rapidly expands both equatorward and poleward. It should be stressed that the maximal latitude is reached a couple of years after the cycle commencement. After reaching the minimal latitude, the spot zone equatorward boundary frequently drifts poleward (*e.g.*, see the cycles 13, northern and southern hemispheres (n.h. and s.h.), 14 (n.h. and s.h.), 15 (n.h. and s.h.), 16 (s.h.)); this phenomenon is visible with increasing sharpness in the second- and higher-level isospotted (*e.g.*, see the cycles

18 (n.h. and s.h.), 19 (n.h. and s.h.), 20 (n.h.), 21 (n.h.), 22 (n.h. and s.h.) and 23 (n.h.)). It should be emphasized that – in further phases of the same cycle – the spot zone again gains the low latitudes from which it retired. On the other hand, after that the spot zone poleward boundary has reached its maximal latitude and begun to retire, spots may reappear at high latitudes, even after a couple of years of quiescence (the semicycles 14 s.h., 14 n.h., 15 s.h., 16 s.h. and 17 s.h. represent cogent exempla).

We may gain a deeper insight on this phenomenology by taking the innermost isospotted, namely the ones delimiting *knots*, into consideration. Figures 1 to 3 show that, in spite of the knots tendency to appear at lower and lower latitudes as the cycle goes on, a knot may actually appear at latitudes either higher or lower than that of previous ones, in a seemingly random way. In some semicycles (for example, cycle 15 s.h., 16 s.h., 17 s.h., 20 n.h., 22 n.h. and 23 s.h.) knots seem arranged into two oblique, roughly parallel *chains*, or *streams*, leaving an underspotted band between them; in these cases, the cycle begins with the activation of a knot at latitude usually not higher than $25 \approx 30^\circ$; this is the first element of a chain of knots which will appear at lower and lower latitudes, forming the butterfly wing equatorward boundary. The last of them appears roughly $50 \approx 60$ CR's after the first one, close to the equator. Accordingly, the slope of the butterfly wing equatorward boundary may be assumed as the rate of the equatorward progression of these knots; its order of magnitude is $\approx 0.5^\circ \text{CR}^{-1} \approx 6^\circ \text{year}^{-1}$. The remnant part of the familiar butterfly wing will be formed by knots belonging to another stream (or to other streams).

3. Discussion and Conclusions

This paper confirms the results described in previous papers by the present author.

The first, relevant result is the discovery of the butterfly wings fragmentation into knots

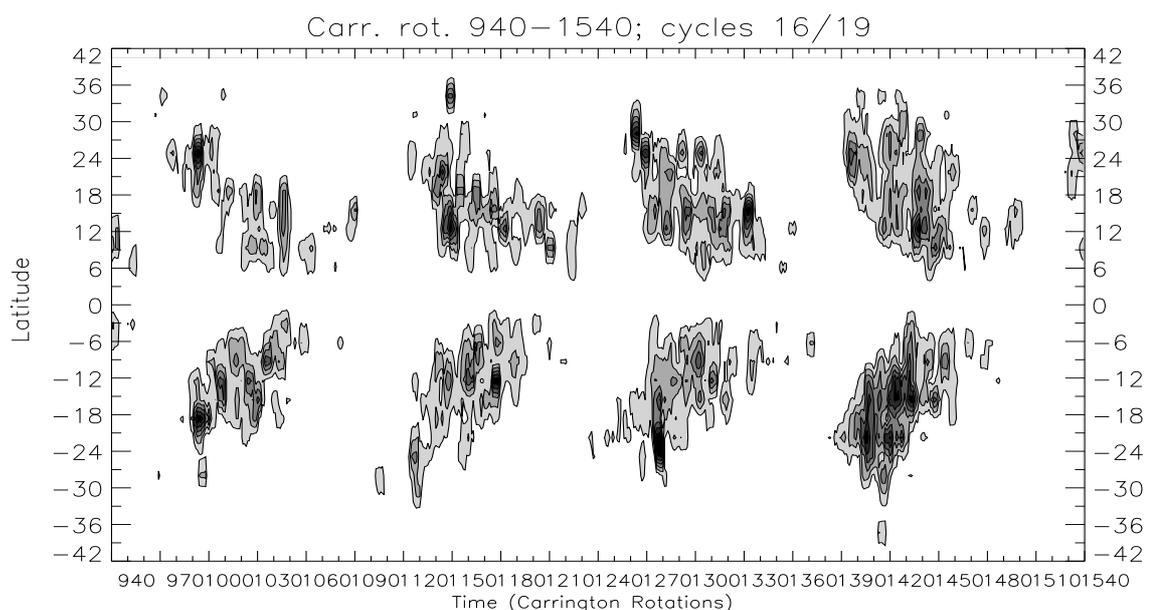


Figure 2. Butterfly Diagram for Carrington rotations 940-1540 (years 1923–1968)

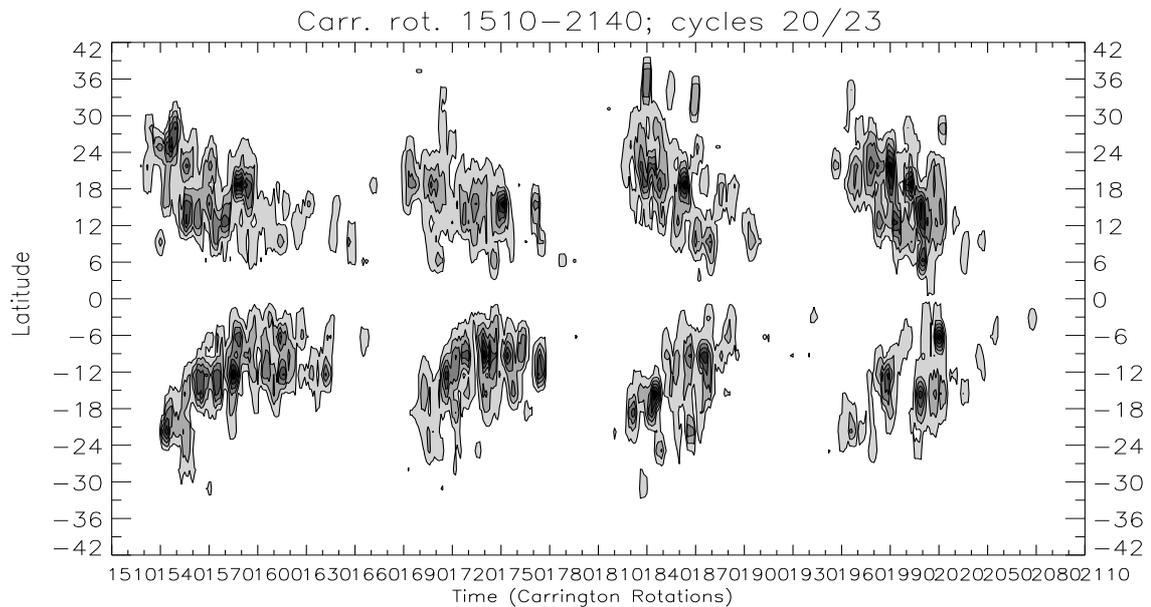


Figure 3. Butterfly Diagram for Carrington rotations 1510-2110 (years 1967-2011)

[24; 25]. This fragmentation is fully compatible with the spotgroups well-known tendency to appear at preferred locations, where they form *complexes of activity* [4; 8] or *sunspot nests* [5]. As a consequence of this new picture of the BD, no continuous, steadily drifting equatorward line can be drawn to represent the “mean latitude of spots”: a line of this kind, indeed, rather than denoting the photospheric zone hosting the spot largest concentration, around which spots are taken to scatter, should be considered but an arithmetic artefact, to which it would be hard to attach any physical significance. If these conclusion will be confirmed, much theoretical work, aimed at predicting the location and evolution of such a mean latitude, should be reconsidered.

The second relevant result is that we begin to understand that the knot distribution in the BD wings obeys some regularities, in spite of the complexity of the processes stochastically acting on the solar dynamo. Describing the spot cycle as a two-wave process throws light on previous results concerning cycles 21 to 23 [21–23]; these works show that the latitudinal drift of the spot zone centroid may be decomposed into genuine equatorward segments and stationary or even poleward ones. The alternance of these prograde/retrograde segments is compatible with the sequence of activations and extinctions of knots belonging to either stream. Indeed, the activation of the second wave, occurring a couple of years after the first one, mimics the first poleward drift of the spot zone centroid; afterwards, other retrograde drifts of the spot zone centroid are the effect of the extinction of a low latitude knot, followed by the activation of a high latitude one; on the other hand, whenever a new, lower-latitude knot becomes active, a high speed prograde phase results. Finally, the extinction of the first wave mimics the last poleward drift of the spot zone centroid.

The pulse-like character of the magnetic flux emergence [8; 17; 23] is probably related to the tachocline oscillating rotation rate [12; 26]. On the basis of the reasonable assumption that, the faster the tachocline rotation, the more efficient the magnetic flux production, one could

conjecture that any sudden augmentation of the photospheric flux is the effect of the tachocline increased rotation rate.

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