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The Butterfly Diagram internal structure

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Abstract. A new graphic representation of the spotgroup distribution with respect to time and latitude is presented. At variance with Maunder's Butterfly Diagram, which registers the mere presence of spotgroups, the diagram presented here accounts for the spotgroup area. It shows that spotgroups aggregate in a few small, heavenly spotted portions ("knots") of the diagram. Each knot is the signature of a photospheric region tightly limited in latitude, active for a short time. The butterfly diagram is but a cluster of knots and the spot zone is the latitude range inside which knots activate. The cycle is a sequence of knots activations and extinctions. Even though knots show the overall tendency to appear at lower and lower latitudes as the cycle goes on, a knot may appear at either lower or higher latitudes than previous ones.
The examination of the knot distribution inside the "butterfly wings" suggests that – at any cycle and at any hemisphere – two "activity waves" drift equatorward at a rate roughly twice the drift rate of the spot zone as a whole.

Key words. Sun: butterfly diagram – Sun: sunspot statistics

1. Introduction

Maunder's Butterfly Diagram (BD) is considered, according to the general consensus of the solar physicists community, a picture of the spot zone so authoritative and reliable that it is usually assumed as a benchmark for many dynamo models of the solar cycle (Charbonneau 2005). Nevertheless, we should remember that the BD usually registers the mere presence of spotgroups, no matter whether they are ephemeral pores or long-lived giant groups (Maunder 1904). Accordingly, the BD is dominated by small, insulated spots, which are by far more numerous than large groups and are distributed over large portions of photosphere (Ternullo 2007c). For the same reason, the BD does not give special visibility to large spotgroups, which should deserve – because of the large amount of magnetic flux they convey – the attention of everybody aiming to know the photospheric magnetic flux large scale distribution.

In Figure 1, this paper presents a new version of the time-latitude diagram, where spotgroups are given relevance proportional to their area. The area is, indeed, a "reasonably unprecise" proxy of magnetic flux, because of the remarkable homogeneity of the magnetic field strength: $1-2$KG, over spot cross section (Solanki, Inhester, & Schüssler 2006). Accordingly, the resulting diagram is expected to give a more faithful picture of the magnetic flux large scale distribution than Maunder's "democratic" method (*one group, one line*) can warrant.

2. Results

Sunspot data have been obtained at INAF – Osservatorio Astrofisico di Catania from 1975 to 2008 (cycles 21 through 23). The daily average values of the spotted area have been computed for any latitude and for any Carrington rotation; afterward, they have been smoothed by a triangular running window, covering 5 Carrington rotations. The resulting data are visualized (Figure 1) by a set of contour lines (*"isospotted"* lines), defined as follows: the outermost line (corresponding to level 0) cuts off points of the BD which are exceedingly under-spotted; level 10 corresponds to the maximal-spottness point; the interval between levels 0 and 10 is divided into 10 equal intervals.

Figure 1 reveals that the spotted area distribution is characterized by remarkable lack of homogeneity: the fraction of the diagram surface entering the second contour line is by far less than 50% of the "butterfly wings" total surface. Inner and inner contour lines form concave arcs which more and more deeply penetrate the butterfly wings, and eventually split into close lines, embracing small portions (*"knots"*) of the time-latitude diagram (Ternullo, 2008). The resulting "leopard skin" appearance of the BD is the signature of the spot tendency to preferentially appear in some photospheric regions tightly limited in latitude, and for short time intervals.

Accordingly, the BD is but a cluster of knots and the spot zone is the latitude range inside which knots form. Spots are scattered about at *as many* latitudes as the knots are, at as many epochs in the cycle. *The cycle history is but the history of a sequence of knots activations and extinctions*. On the one hand, we may safely state that knots show the *tendency* to appear at lower and lower latitudes; on the other hand, we should be aware that this is but a *tendency* and that the latitude of a given knot may be either higher or lower than that of the previous one. This implies that, as a knot becomes active, the role of "active latitude" abruptly passes from a latitude to another, in a way which could be called *a "latitudinal flip-flop"*.

An inspection of Figure 1 reveals that, as regards cycle 23 (southern hemisphere), knots are arranged so as to form two oblique "chains", running roughly parallel to the spot zone equatorward and poleward boundaries, and leaving an underspotted strip (a *"depletion channel"*) between them, namely, where the ill-defined "spot average latitude" would be expected.

This observation has suggested me to define an algorithm to objectively and systematically investigate whether, in other cycles, a similar *"depletion channel"* may be recognized. To accomplish such a goal, any point in the BD (that is, any couple "Carrington Rotation + latitude") has been considered as the base point of a pencil of "channels", each one extended 3° latitudinally, with slopes finely spanning the interval 0 through $8° y^{-1}$. For each channel, the spot density inside it and in two 5°-wide strips on either side of it has been calculated. Thanks to this approach, it can be recognized that, for each semicycle, several channels exist inside which the spot density is significantly lower than in both adjacent strips. For any semicycle, the most sharply defined channel – that is, the channel for which the spot density difference is maximally significant – has been visualized. For all these channels, the spot density difference exceedes 7 through $\approx$ 16 times the standard error affecting the difference. These channels have slopes in the range 3.5 through $7.4° y^{-1}$, corresponding to 1.35 through $2.9 ms^{-1}$.

3. Discussion and conclusions

The spotgroup tendency to preferentially appear in some parts of the photosphere has been repeatedly described. For example, Bumba & Howard (1965) and Castenmiller et al. (1986) coined the expressions *complexes of activity* and *sunspot nests* to denote the resulting spot aggregations, respectively; Gaizauskas et al. (1983) described the "*pulse-like*" character of the magnetic flux emergency; Rabin et al. (1991) described *"pulses of activity"* for cycle 21. Expressions as *sunspot nests* and *pulses of activity* emphasize the compactness of the

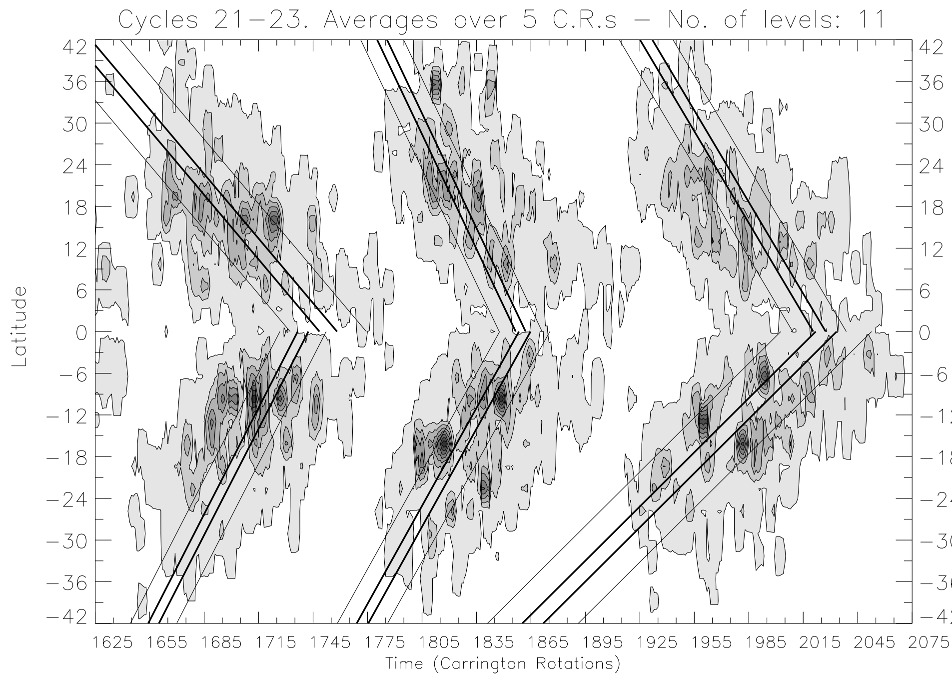

Fig. 1. The Butterfly Diagram for Carrington rotations 1625-2075 (years 1975-2008)

birth sites of clustering active regions and their short lifetime, respectively: these are the characteristics we find in our knots.

The aforementioned *"latitudinal flip-flop"* sharply rules out the old picture pretending that the BD bidimensional character is the effect of the spot "natural" dispersion about an average latitude continuously drifting equatorward, as it has been explicitely described, for example, by Waldmeier (1966) and Kopecký (1970) or suggested by the usage of common expressions as "the average latitude of activity" or "the mean latitude of the active regions". The old picture describes a single activity wave, whose drift rate is $\approx 2.2 \pm 0.28^{\circ}\mathrm{y}^{-1}$ (Waldmeier 1939; Hathaway et al. 2003).

On the other hand, the findings described in this paper support the following scenario: in each semycicle two waves of activity run through the photosphere, from high latitudes toward the equator, at a rate given by the depletion channel slope. That implies that the time any wave spends in its run is roughly 4 through 8.5 years. The first activity wave marks the beginning of the cycle. The second one starts after a couple of years and, for a part of the cycle, both waves are simultaneously active. Because of this time lag, spotgroups of different waves lie at different latitudes and are separated by an underpopulated, ≈ 7 through 10° wide belt. The resulting bimodality of the sunspot latitudinal distribution has been described for cycle 21 by Ternullo (1990, 1994).

In the light of these findings, the poleward displacements of the spot zone described by Norton & Gilman (2004) and, for cycles 21 through 23, by Ternullo (1997, 2001, 2007a,b,c) become comprehensible: 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 (that is, a *first-wave knot*), followed by the activation of a high latitude one (a *second-wave* *knot*); 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 another poleward drift of the spot zone centroid. The end of the cycle coincides with the extinction of the second wave. The pulse-like character of the magnetic flux emergency is probably related with the tachocline oscillating rotation rate (Howe et al. 2001; Toomre et al. 2003). 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 brusque augmentation of the photospheric flux is the effect of the increased tachocline rotation rate. Indeeed, the time intervals between pulses of activity is compatible with the periodicity (1.3 through 1.5 years) of the tachocline rotation rate oscillations.

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