Astron. Astrophys. 327, 361–364 (1997)

ASTRONOMY
AND
ASTROPHYSICS

Distribution of sunspot groups from asymmetric rising flux loops

M. Schüssler and H. Wöhl

Kiepenheuer-Institut für Sonnenphysik, Schöneckstr. 6, D-79104 Freiburg, Germany

Received 8 April 1997 / Accepted 9 June 1997

Abstract. Rising magnetic flux loops in the solar convection zone develop an asymmetric shape with a flat preceding part and a steeper following part with respect to the direction of solar rotation. By a statistical analysis of newly forming sunspot groups we test the conjecture that this geometrical asymmetry leads to an asymmetric distribution of secondary spot groups originating from the legs of the same rising flux loop as the primary group, which develops out of the loop summit. We find that $\sim 10\%$ of all sunspot groups actually develop secondary groups within $\pm 20^\circ$ longitude distance from the primary group and within one day after its emergence. Those secondary groups related to small primary groups (area $<$ 100 millionths of the solar hemisphere) are predominantly located on their eastern (following) side, while for larger primary groups the secondaries are more numerous on their western (preceding) side. Both results are consistent with the geometrical asymmetry developed by rising magnetic flux loops.

Key words: Sun: activity – Sun: interior – Sun: magnetic fields – sunspots – flux tubes

1. Introduction

Numerical simulations of rising magnetic flux loops in the solar convection zone predict the development of an asymmetric shape in these loops as a consequence of solar rotation and conservation of angular momentum (Moreno-Insertis et al. 1994, Caligari et al. 1995): the part of the loop following with respect to the direction of rotation (the f-wing) is more vertical (i.e., closer to the radial direction) than the preceding side (the p-wing). Fig. 1 shows an example of this effect.

The geometical asymmetry between the p- and the f-wings has observable consequences for newly emerging active regions, namely, asymmetries of the magnetic flux distribution and of the proper motions for the two polarities (e.g., Harvey & Martin 1973, Van Driel-Gesztelyi & Petrovay 1990, Strous et al. 1996). Here we investigate whether the emergence of a sunspot group entails the appearance of nearby secondary magnetic regions within a few days following the primary eruption and whether the geometrical asymmetry of the underlying flux loop affects the longitude distribution of such secondary active regions.

The basic idea is illustrated schematically in Fig. 2: secondary loops in the upper part of the wings of the main loop form due to Parker instability or when fragments of the main loop are carried by intense convective upflows. The emergence of these loops at the surface leads to secondary magnetic regions closely associated in space and time to the formation of the primary region. Since the p-wing of the original loop is hiher up in the convection zone and more extended in longitude we expect to find more such secondary loops in that part (westward from the primary region) than in the f-wing (on the eastern side). In order to test this hypothesis, we carry out a statistical analysis of observed sunspot groups.

2. Data analysis

We use the *Greenwich Photoheliographic Results* (1874 - 1976) and the sunspot group data from the *Solar Geophysical Data* for the years 1977 - 1981. Both sets provide observing dates and times, group numbers, heliographic positions, and areas of sunspot groups. Areas (for umbrae and penumbrae) are given as group totals in millionths of the solar hemisphere. The data comprise a total of about 180,000 daily observations of 37,341 different sunspot groups.

We select those sunspot groups which were first observed within ±10° longitude of the central meridian ('primary groups'). Thus we can safely assume that these groups actually emerged at the surface in this longitude range and minimize geometrical and rotational effects. We then search for other groups ('secondary groups') which were first observed at the same or the following day and record their positions relative to the longitude of the first group. We restrict ourselves to ±20° longitude distance from the primary group since for larger distances the influence of the visibility function and of solar rotation on the observed longitude distribution of sunspot groups can no longer be neglected (e.g., Kopecký et al. 1985). For the same reason we do not consider longer time intervals between the appearance of primary and secondary sunspot groups.

Since primary and secondary sunspot groups originate from the same rising flux loop they should emerge at about the same

---

Send offprint requests to: M. Schüssler

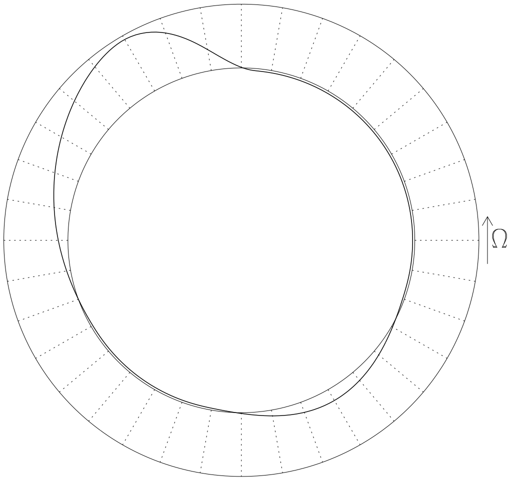

Fig. 1. Asymmetric geometrical shape of a rising flux loop in the simulations of Caligari et al. (1995). Shown is a projection of the three-dimensional tube on the equatorial plane as seen from above the north pole. The non-emerging part of the flux tube is anchored in the overshoot region below the convection zone. The dashed radial lines are drawn at longitude intervals of 10°.

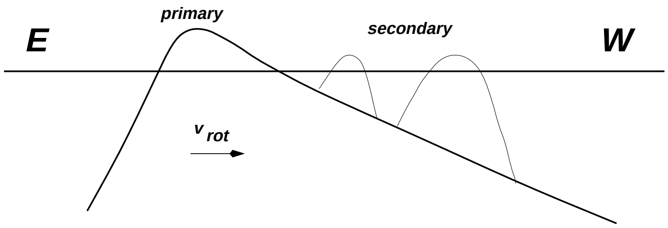

Fig. 2. Schematic sketch of the formation of primary and secondary spot groups from a rising flux loop. The solar surface is indicated by the horizontal line. The asymmetric shape of the loop with its flatter and more extended preceding part favors the emergence of secondary loops westward of the primary spot group.

latitude. Allowing for a tilt angle of the loop (with respect to the east-west direction) of up to 10° (Howard 1991) we restrict the latitudinal distance of secondary groups from the primary group to ±5°.

We have defined primary and secondary groups in an operational way, depending on the location of their first appearance. Consequently, we cannot say beforehand whether a given 'primary' group is actually primary in the sense of Fig. 2. We suppose that groups that develop a large area in their further evolution are more likely to be primary in the physical sense than groups that stay small, a number of those probably being secondary groups to a primary group emerging outside of our search interval. We therefore expect that the effect we are investigating is more pronounced for primary groups of large area. For that reason we determine the distribution of the secondary groups as a function of the maximum area developed by the primary groups during their further evolution (as long as they are visible on the disk).

Table 1. Number of secondary sunspot groups emerging on the same day as primary groups that have been first detected within ±10 deg longitude from the central meridian. The secondary groups are counted in the longitude intervals $(-20°, -10°)$, $(-10°, 0°)$, $(0°, 10°)$, and $(10°, 20°)$, respectively, relative to the position of the primary group; the centroids of these intervals are indicated. SGs are only considered within ±5° latitude distance from the corresponding PG. The last two columns give the total numbers of secondary groups that have emerged eastward and westward, respectively, from the primary group. The results are given as a function of the maximum area A_p (in millionths of a solar hemisphere) developed by the primary group.

A_p [μH]	$-15°$	$-5°$	+5°	+15°	East	West
$0-20$	57	42	29	42	99	71
$20-50$	18	19	8	12	37	20
$50-100$	8	6	6	6	14	12
$100-500$	5	4	11	16	9	27
$500-5000$	3	1	2	4	4	6

Table 2. Same as Table 1, but for secondary groups emerging one day after the first detection of the primary group.

A_p [μH]	$-15°$	$-5°$	+5°	+15°	East	West
$0-20$	10	11	7	10	21	17
$20-50$	11	11	8	8	22	16
$50-100$	7	5	2	4	12	6
$100-500$	8	10	10	7	18	17
$500-5000$	2	0	0	1	2	1

3. Results

Within ±10° longitude from the central meridian we have 3793 newly emerging sunspot groups. In a longitude interval of ±20° and a latitude interval of ±5° from these primary groups (PGs) we find 299 secondary groups (SGs) emerging on the same day as the PG and 132 SGs appearing on the following day. Hence, SGs are formed for $\sim$ 10% of the PGs and they appear mainly within about one day after the emergence of the PG.

The distribution of longitude seperations of the SGs from the corresponding PGs is given in Table 1 for SGs appearing on the same day as the PGs; for SGs emerging on the next day the results are shown in Table 2. We have binned the longitude separations of the SGs into four intervals, each 10° wide with centroids at $-15°$, $-5°$, +5°, and +15°, respectively. The last two columns in the Tables give the total numbers of SGs that emerge eastward and westward, respectively, of the corresponding PG. The distributions are given as a function of the maximum area, A_p (in millionths of a solar hemisphere, μH) of the PGs.

There are more SGs emerging eastward of small PGs ($A_p < 100\mu$H). For PGs with larger area the secondaries emerge preferentially on their western (preceding) side if they appear on the same day as the primary (Table 1); there is no east-west preference for SGs emerging the day after the appearance of a

Table 3. Same as Table 1, but for secondary groups emerging 180 days after the first detection of the primary group. No physical relation between primary and secondary groups is expected in this comparison case.

A_p [μH]	$-15°$	$-5°$	$+5°$	$+15°$	East	West
$0 - 20$	33	37	34	30	70	64
$20 - 50$	14	9	15	6	23	21
$50 - 100$	5	3	4	7	8	11
$100 - 500$	6	8	8	9	14	17
$500 - 5000$	2	6	1	1	8	2

Table 4. Number of secondary groups emerging eastward (E) and westward (W), respectively, for small ($0 - 100\mu$H) and large ($100 - 5000\mu$H) primary sunspot groups. The first pair of columns corresponds to secondary groups emerging on the same day (+0d) as the primary group, the second pair of columns refers to groups emerging on the following day (+1d); the third pair of columns gives the result for the comparison case of groups emerging after 180 days.

	+0d		+1d		+180d	
A_p	E	W	E	W	E	W
$0 - 100$	150	103	55	39	101	96
$100 - 5000$	13	33	20	18	22	19

large primary group (Table 2). For comparison, we have performed the same analysis for groups appearing 180 days after the emergence of the PGs. Such groups should have no physical relation to the primary groups that surfaced half a year earlier, so that we expect no significant asymmetry in their distribution. In fact, the results of this test as given in Table 3 show an almost symmetric distribution except for the largest PGs, but the total number of these is small.

The dependence of SG location on the size of the their PGs is seen even more clearly by summing the SGs for PGs with areas below and above 100μH, respectively, and considering eastward or westward emergence only. In total we have 3108 PGs with $A_p < 100\mu$H and 685 PGs with $A_p > 100\mu$H. Table 4 gives the numbers of westward and eastward SGs, respectively, which appear on the same day (first pair of columns), the next day (second pair), and after 180 days (last pair). This table contains the essence of our result: there is a preference for *eastward* emergence of SGs related to *small* PGs ($A_p < 100\mu$H) and a preference for *westward* emergence for SGs appearing on the same day as *large* PGs ($A_p > 100\mu$H). These asymmetries are statistically significant on a level of two promille (assuming a binomial distribution for the eastward/westward location of the SGs). No significant (below the one percent level) east-west asymmetry is found for SGs appearing one day after the emergence of the PG; neither do we find any significant asymmetry for SGs appearing 180 days later, when there is no longer any physical connections between PGs and SGs.

4. Discussion

The small number of SGs found in our analysis indicates that secondary loop formation is not a common process in the development of a rising magnetic flux loop. Only $\sim 10\%$ of the PGs have associated SGs, most of them emerging on the same day as the PG. Nevertheless, the distribution of the SGs as summarized in Table 4 indicates that there are indeed asymmetries between the numbers of secondary groups emerging to the east and to the west of a given sunspot group. For primary groups with a maximum observed area above 100 μH the asymmetry is in accordance with the expectation expressed in Fig. 2: more SGs emerge westward, i.e., in the preceding part of the PG. However, the asymmetry in longitude distribution of SGs is reversed for PGs below 100 μH. How can we understand the different behavior for small and large PGs ?

Firstly, the numerical simulations of Moreno-Insertis et al. (1994) show that thicker flux tubes develop a larger geometrical asymmetry between the two legs of a rising loop since they are less prone to the aerodynamic drag force counteracting the effect of the Coriolis force. We conclude from their results that the effects of asymmetry should be most pronounced for flux tubes with a substantial amount of magnetic flux, say $\Phi_{\rm m} \gtrsim 10^{22}$ Mx, corresponding to a rather large sunspot group. Assuming a field strength of 3000 G at the surface this value gives an area of about 100 μH. Such a thick tube is probably also not much affected by fluctuations like local convective flows and should therefore retain its asymmetric shape for a sufficiently long time to result in an asymmetric distribution of the developing secondary loops such that SGs are more likely to be found on its preceding side.

Secondly, as already discussed in Sect. 2, sunspot groups that develop a large area in the course of their evolution are more likely to be really ‘primary’ (in the sense of Fig. 2) rather than secondary groups of another group. Assume that a significant part of the PGs with small flux in our sample are in fact secondaries of a main group emerging outside our search interval of $\pm 10°$ from the central meridian. If an asymmetric distribution in the sense of Fig. 2 prevails, then we should expect an *easterly* dominance of groups associated to this false ‘primary’ group, which itself is one of a number of secondaries on the preceding (westerly) side of the main group.

We conclude that both the easterly dominance for PGs with small area and the westerly dominance for PGs with large area are in accordance with the geometry and asymmetry of secondary loop formation indicated in Fig. 2, assuming that large PGs are primary emergences of a large loop while many small PGs are in fact secondary eruptions from a larger loop whose main emergence is outside our search interval.

Geometric or rotational effects as well as the influence of group evolution on the distributions have deliberately been minimized by the restriction of our search to regions newly emerging near the central meridian so that they cannot provide an alternative explanation for the asymmetric distributions found here. On the other hand, this necessary restriction leads to rather small numbers of sunspot groups that went into our analysis, particularly for the larger areas. We should therefore be cautious regarding the statistical significance of the results (although they formally pass the standard tests), particularly since we cannot exclude systematic effects introduced by the observers. For instance, if the persons analyzing the Greenwich observations routinely checked whether a small group newly detected on the plate for a given day can be traced back to the plate taken on the day before, this could lead to a systematic easterly skew in the distribution, even very near to the equator. Also the well-known asymmetry between the preceding and the more widespread and diffuse following parts of sunspot groups may lead to a tendency for the observer to count new activity more often as separate groups in the east (following part) than in the west (preceding part), although this bias is probably not very important for the very young sunspot groups considered in our analysis. Such effects could possibly affect our interpretation of the easterly dominance for small primary groups, but they would even strengthen the significance of our result for large groups (which may suffer from the small numbers involved, however).

Since our statistical treatment is already based on nearly all available sunspot data, there is no possibility to strengthen our conclusions by using a larger data basis. Neither does the small number of SGs detected allow a more detailed analysis aiming at, for instance, detecting the tilt angle or the different longitudinal extension of the preceding and the following parts of the rising flux loop. A detailed evolutionary study of a number of individual active regions, including magnetograms to infer magnetic polarities, is required to further clarify the relation between primary and secondary sunspot groups and their connection with asymmetric magnetic flux loops in the convection zone.

5. Conclusion

The longitude distribution of secondary sunspot groups relative to the corresponding primary groups is consistent with the expectation based on the rotationally induced asymmetrical shape of a magnetic flux loop rising through the convection zone.

Acknowledgements. We are grateful to Drs. U. Grossmann-Doerth and F. Moreno-Insertis for helpful discussions and comments on a draft version of the paper.

References

Caligari P., Moreno-Insertis F., Schüssler M. 1995, ApJ 441, 886
Harvey K.L., Martin S.F. 1973, Sol. Phys. 32, 389
Howard R.F. 1991, Sol. Phys. 136, 251
Kopecký M., Kuklin G.V., Starkova I.P. 1985, Bull. Astr. Inst. Czechosl., 36, 189
Moreno-Insertis F., Caligari P., Schüssler M. 1994, Sol. Phys. 153, 449
Strous L.H., Scharmer G., Tarbell T.D., Title A.M., Zwaan C. 1996, A&A 306, 947
Van Driel-Gesztelyi L., Petrovay K. 1990, Sol. Phys. 126, 285

This article was processed by the author using Springer-Verlag LaTeX A&A style file *L-AA* version 3.