Variations of the Internal Asymmetries of Sunspot Groups during Their Decay

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\textbf{Abstract}

The aim of the present study is to show the varying asymmetries during the decay of sunspot groups. The source of input data is the SOHO/MDI-Debrecen Database sunspot catalog that contains the magnetic polarity data for time interval 1996–2010. Several types of asymmetries were examined on the selected sample of 142 sunspot groups. The leading–following asymmetry increases in three phases during the decay and exhibits anticorrelation with size. It is also related to a hemispheric asymmetry: during the decay, the area asymmetry index has higher values in the southern hemisphere, which may be due to the higher activity level in the southern hemisphere in cycle 23. The total umbral area is inversely proportional to the umbra/penumbra ratio, but it is directly proportional to the umbral decay rate. During the decay, the umbra/penumbra (U/P) ratio decreases unambiguously in the trailing parts but in most cases in the leading parts as well. The U/P variation is a consequence of the different depths of umbral and penumbral fields.

\textit{Unified Astronomy Thesaurus concepts: Sunspot groups (1651)}

\section{1. Introduction}

The development of solar active regions (ARs) until the maximum state and their decay afterward are governed by different mechanisms. The detailed description of these events is important for the understanding of the complex system of interactions between solar magnetic and velocity fields. The investigation of sunspot decay started with the study of single spots. Cowling (1946) published the theoretical consideration that the decay of a spot cannot be caused merely by diffusion; the surrounding velocity fields have to play a definitive role in it. This has been worked out in detail in Petrovay & van Driel-Gesztelyi (1997). Cowling (1946) also compared the evolutionary curve of two groups with their magnetic-life histories and obtained that the magnetic field increases very rapidly and reaches its maximum almost in the same time as the area. Hagenaar & Shine (2005) presented details of the moving magnetic features (MMFs) by tracking eight sunspots. MMFs are small knots around the sunspots with roughly 10\textsuperscript{3} km diameter that transport magnetic flux away from the spots. Komm et al. (2009) studied the convective motions and the sunspot decay on a sample of 788 ARs and found that the strong upflow changes to downflow at a certain depth during the decay. Hagenaar & Shine (2005) pointed out that there are more MMFs around the larger spots by studying eight sunspots.

The decay of sunspot groups is a more complex series of events and interactions. In the model of Piddington (1975) the sunspot groups start to decay when the flux ropes lose their twists. Thus, unwinding of the flux ropes frays the rope itself. The large, long-lived sunspots are bound with an annular moat and measured an outward velocity in the moat. When the spots start to decay, small magnetic knots can be observed moving outward across the moat. These knots carry away the flux from the spot. This model describes strong plasma control of the flux tube. Norton et al. (2017) studied the decay in some cases and found a higher decay rate in the following part and obtained a relation between the rate of the MMFs and the leading/following decay rates. The average value of the decaying flux is in agreement with the rate obtained by Hagenaar & Shine (2005). Deng et al. (2007) observed a decaying follower sunspot over 6 days and pointed out that the umbra/total areas increased from 15.9\% to 19\% during the decay, showing that the umbra decays more slowly than the penumbra. Although the decay rate was found as almost constant, the decay process is not uniform. They described the decay as a three-step process. First, the fragmentation of the sunspot can be observed, and then the flux cancellation of MMFs that encounter the opposite-polarity network at the edge of the moat region, while at the end the flux is transported by MMFs. Gafeira et al. (2014) followed the evolution of four ARs by using intensitygrams obtained by the Helioseismic and Magnetic Imager on board the Solar Dynamics Observatory. They found that the largest contributor to the total area decay rates of spots are the decay rates of the penumbra, while the umbral decay rates are much lower. These results are in agreement with the observations of Schlichenmaier et al. (2010).

Rempel & Cheung (2014), in their theoretical simulation, obtained that lifetimes of sunspots are too short in the absence of a penumbra. They concluded that either the penumbra may stabilize the surface layers of sunspots or it delays the fragmentation of the subsurface layers of sunspots.

There are some works that analyze different asymmetries during the evolution of ARs. Javaraiah (2012) examined the rates of growth and decay of sunspot groups and pointed out differences between the hemispheric values. Some other works studied the tilt angles of sunspot groups and their variations during the decay and observed a difference between the northern and southern values (Li & Ulrich 2012; McClintock & Norton 2013), while Howard (1993) investigated the dependence of the decay of sunspot groups on axial tilt angles. Murakózy et al. (2014) studied the area and number asymmetries of sunspot groups at their maximum states and...
pointed out an asymmetry in the compactness of groups, i.e., the number of spots tends to be smaller, while their mean area is larger in the leading part at the maximum phase.

Martinez Pillet et al. (1993) obtained that the ratio of the total area to the umbra area is about 4–6 and noted that this parameter is independent of the evolutionary phase of the spot except the very last stage, when the leading umbra is the only remnant of the sunspot. Deng et al. (2007) also analyzed the UP/U ratio during the decay of NOAA AR 10773 and found that it varies between 5 and 6. Carrasco et al. (2018a) studied the decay and the U/P ratio of sunspots during the Maunder minimum and revealed that the value of the U/P ratio varies between 0.15 and 0.25, and the higher the U/P ratio, the faster the decay of the sunspot. Jha et al. (2019) obtained 5.5–6 for the P/U value and pointed out that this ratio is independent of cycle strength, latitude, and cycle phase. The results of Hathaway (2013) are in agreement with this; however, he found that this ratio increases with the increasing total sunspot group area. Brandt et al. (1990) studied 126 sunspot groups observed around 1980 and pointed out that the U/P value is 0.24 for small spots and 0.32 for large spots. Carrasco et al. (2018b) found different behavior in the variation of U/P ratio of the small and large groups by using the Royal Greenwich Observatory series. The larger groups do not show significant changes from year to year, while the smaller groups do. Hoyt & Schatten (1997) noted that the rate of sunspot decay is proportional to the convective velocity, which means that the higher the convective velocities, the higher the U/P values and the faster the sunspot decay.

The aforementioned investigations dealt with the decay process of sunspot groups, and some of them focused on the internal process as well. After the calculation of the distinct decay rates (Muraközy 2021), this study aims to describe the variation of the asymmetries within the sunspot groups during their decay.

### 2. Data and Methods

#### 2.1. Observational Data

The present study has been made by using the SOHO/MDI-Debrecen Database (Baranyi et al. 2016), which is one of the sunspot catalogs made in the Debrecen Observatory and contains sunspot data from 1996 until 2010. This database has about 1.5 hr temporal resolution, which is allowed by the observations of the Solar and Heliospheric Observatory (SOHO) spacecraft, and besides the area and position data contain also magnetic data for each observable sunspot group, as well as for each sunspot within them. Thus, the leading and following parts of the sunspot groups can be distinguished, and the temporal resolution makes it possible to track the evolution of the groups and their parts.

In order to select from this huge database those sunspot groups that are definitely in the decay phase, the following strict criteria were set. The sunspot groups should have two opposite-polarity parts at the time of the maximum area. The development area has to be observed at least for two days while the decaying area has to be tracked at least during 4 consecutive days after the maximum, and the first and last observed areas could be at most 40% of the maximum area. All three areas (total area, leading and following areas) have to decrease during the decay phase, and these criteria were visually inspected in each case as well. The total number of the selected sample is 142.

#### 2.2. Method

In this study the normalized asymmetry index (AI) is used. The asymmetry index between the leading and following part of sunspot groups is calculated as

$$\text{AI}_x = \frac{x_l - x_f}{x_l + x_f},$$

where $x_l$ and $x_f$ represent the parameter of the leading and following parts, respectively. This property may be the area of the sunspot groups ($A_{up}$) or that of the umbrae ($a_{up}$). The decay phase of the sunspot groups will be characterized by the area decay phase (ADP), which is determined for each observational time of the groups:

$$\text{ADP} = \left(1 - \frac{a}{A}\right) \times 100,$$

where $A$ is the maximum area of the group and $a$ is the observed area. If the value of the asymmetry index is 0, that means that the parameters of the leading and following parts are equal, while 1 and $-1$ mean that the following or leading part is missing and the relevant parameter only refers to the existing part. ADP = 0 marks the maximum value of the sunspot group’s area (see Table 1).

These asymmetry indices are calculated for each observational time or ADP. Then, the obtained asymmetry indices are averaged over 10% bins of the ADP. Although in typical cases the mean size of the follower spots is smaller than that of the leader ones (left panel of Figure 1), there are exceptions where

| Table 1 |
|--------------|--------------|--------------|--------------|--------------|
| NOAA AR 8086; $A_{up} = 432$ MSH | NOAA AR 9037; $A_{up} = 340$ MSH |
| $a_{up}$ | ADP$_{up}$ | Lead. $a_{up}$ | Foll. $a_{up}$ | AI$_{up}$ | $a_{up}$ | ADP$_{up}$ | Lead. $a_{up}$ | Foll. $a_{up}$ | AI$_{up}$ |
| 432 | 0 | 243 | 189 | 0.125 | 340 | 0 | 133 | 207 | $-0.218$ |
| 400 | 7.407 | 239 | 161 | 0.195 | 315 | 7.353 | 126 | 189 | $-0.200$ |
| 299 | 30.787 | 199 | 100 | 0.331 | 251 | 32.059 | 94 | 137 | $-0.186$ |
| 225 | 47.917 | 180 | 45 | 0.6 | 174 | 48.824 | 60 | 114 | $-0.310$ |
| 132 | 69.444 | 129 | 3 | 0.955 | 102 | 70 | 32 | 70 | $-0.373$ |
| 47 | 89.120 | 47 | NO | 1 | 12 | 96.471 | NO | 12 | $-1$ |

Note. $A_{up}$ is the maximum area of the group in millionths of solar hemisphere (MSH) at ADP 0. Columns of the sets are as follows: $a_{up}$ means the observed umbra +penumbra area measured in MSH, ADP is calculated by using Equation (2) measured in %, areas of the leading and following parts in MSH, while the last column describes the area asymmetry index calculated by using Equation (1). NO means that the leading or following sunspot already cannot be observed at all.
the mean size of following spots is larger than that of the leader ones (right panel of Figure 1); these are characterized by negative asymmetry index. These data, i.e., the ADP, and the $AIA_{up}$ can be found in Table 1 for the NOAA AR 8086 and NOAA AR 9037. The table contains only six rows for each AR after their maximum area of the whole group. ADP = 0 denotes the maximum area of sunspot groups.

3. Results and Discussion

In a previous paper (Muraközy 2021) it has been shown that the leading and following parts of sunspot groups decay with different rates. After the determination of their decay rates, the dynamics of the variation of the two parts are calculated. First of all, the area asymmetry index is studied for both the whole sunspot groups and only the umbrae.

The panels of Figure 2 show the combined history of the decay and the asymmetry variation of sunspot groups after their maximum state; the area asymmetry indices are averaged over 10% bins of the ADP. The sunspot groups of positive and negative asymmetries (according to Equation (1)) are plotted separately. The left columns show all sunspot group sizes together. It is a common property of the diagrams that the increase of the asymmetry begins at about 35% of the area decay, but it is conspicuous that after this the variation is steepest for the umbral areas of sunspot groups of positive asymmetry (upper half of the bottom panel in the left column). This can be considered to be the most typical case; the process starts at the maximum state with very small asymmetry that reaches the value of $+1$ at the end with a single leading spot. In contrast, the sunspot groups of negative area asymmetry (bottom panel, lower diagram) do not end with asymmetry of $-1$, i.e., with only a follower polarity.

Overall, it can be said that the leading/following area ratio of the maximum, which is near 0, means that the area of both parts is almost equal and is preserved during the first phase of the decay. This is followed by the steeper variation when the smaller part of the group starts to disappear, and in the last phase of the decay it almost or totally disappears and the total umbral area is dominated by only the part with a larger area.

Figure 1. Variation of the area asymmetry indices of NOAA AR 8086 (on the left) and NOAA AR 9037 (on the right) after their maximum areas during the decay phase. The red circles mark those data that are in Table 1.

Figure 2. Left: dependence of the normalized asymmetry index on the ADP calculated for the total (umbra+penumbra) areas (top panel) and the umbral area (bottom panel). The numbers of the positive/negative cases are marked at the left corners of the panels; the numbers of positive cases are significantly higher. Right: the same as in the left panels, but the asymmetry indices are calculated for three area ranges.
During the first phase, the area of the leading/following part is about 50% larger than the area of the following/leading part. This ratio increases during the decomposition and reaches about 0.7 in the case of the total area, while this value is higher, about 0.9, in the case of the umbrae. In an earlier work (Muraközy et al. 2014) similar variation has been observed in the asymmetric emergence of the leading–following parts. Deng et al. (2007) also described the decay as a three-step process, but only on the decay of one following sunspot. They identified the three steps with fragmentation, the flux cancellation, and the flux transport by MMFs, respectively.

The right column shows the same variations in three area ranges. For umbral–penumbra areas they are indicated in the top panel. The umbral area ranges are defined as one-fifth of the total area ranges as in a previous paper (Muraközy 2021); this ratio was found at the time of maximum. It is conspicuous that the most typical decay pattern is exhibited by the largest sunspot groups, where the asymmetry is close to zero at the maximum area; its absolute value starts rising around one-third of the ADP of the group, and at the end it reaches the final values of about +1 or −1. The time profiles of the smaller groups are more flattened, especially those of negative asymmetry.

The two hemispheres have been examined separately. Figure 3 shows the umbral ADP variation during the decay phase by distinguishing the types of asymmetries and the hemispheres; thus, the diagram is a more detailed version of the bottom left panel of Figure 2. The additional information can be read from the bottom panel of the diagram, showing the data of groups of negative asymmetry. Here the data of the southern hemisphere follow the standard time profile: unambiguous strengthening of the asymmetry starting at one-third of the decay time interval and ending close to −1, while the data set of the northern hemisphere exhibits a weaker variation. This explains the similarly weak variation of the combined north–south data in the negative domain of the bottom left panel of Figure 2.

These distinctions permit a conjecture. The parallel course of asymmetry variation and decay takes the above-formulated standard form typically in large sunspot groups even in the less frequent cases of negative asymmetry. This can be seen in the bottom right panel of Figure 2 in its positive and negative halves. On the other hand, Figure 3 also presents an indirect evidence for this; the time profile of negative asymmetries in the southern hemisphere corresponds to this pattern. The southern hemisphere is more active in most of solar cycle 23 covered by the applied data (Chowdhury et al. 2013), and it also predominates in the applied sample shown in Figure 3; furthermore, the umbral area asymmetry index is always higher in the southern hemisphere. This may imply that the strong flux ropes emerging from the strong toroidal magnetic fields, presumably from deeper layers, are subject to a different set of impacts than the smaller sunspot groups. This may be a consequence of the higher sunspot activity in cycle 23. Several hemispheric asymmetries have been pointed out, e.g., in the decay rate (Muraközy 2021) or in the tilt angles of ARs (Li & Ulrich 2012; McClintock & Norton 2013).

The average area of the sunspot group is also studied (Figure 4). The three panels concern different sizes of sunspot groups, from the smallest ones (\(A_{\text{up}} < 100\) MSH) to the biggest groups (\(A_{\text{up}} > 300\) MSH). The shapes of the courses are similar in the cases of the smallest and the medium-size sunspot groups. These groups show that the average sizes of sunspots of the leading and following parts decrease simultaneously until 45% of the ADP, where they reach their plateaus, and after 75% of the ADP they decrease again. The average sizes of the leading spots are higher during the whole decay in all three cases. The course of the decay is somewhat different in the case of the biggest groups. Here the average sizes of spots show an increasing trend after the short first phase of decay. This is caused by the sudden drop in the number of spots, i.e., the smallest spots disappear around 70% of the ADP, while the largest spots survive. This is more pronounced in the case of the leading spots. At the end of the ADP, the average sizes of sunspots will be nearly the same in each case. The area ratio of the leading/following spots is different in these three area ranges. The ratio decreases toward the end of decay in the cases of the smallest and the middle groups, but in the case of the biggest groups this ratio increases in the middle of ADP. It can also be seen that the higher the area of groups, the smaller the

![Figure 3](image-url). Hemispheric variation of the normalized umbral area asymmetry index calculated between the leading and following parts (\(A_{\text{up}}\)) during the decay of the sunspot groups. The northern hemispheric values are marked by filled rhombuses, and the southern values are depicted by open rhombuses. The top and bottom panels depict the cases of positive/negative asymmetries; the two hemispheres are distinguished in both subsets.

![Figure 4](image-url). Mean sunspot area of the leading part (filled circles) and following part (open circles) averaged over 10% bins of the decay phase of the whole group. 0% means the maximum area of the groups. The three panels show the variations of three different area ranges.
The ratio between the leading and following spots around the maxima. The total area of leading spots is about twice larger than that of the following ones in smallest groups, and this ratio is about 1.5 in medium and large groups.

The penumbrae (P) are formed by the strongly inclined field lines of sunspots at the surface layers (Panja et al. 2021), so their decay may be controlled by processes different from those of the umbrae (U), thereby influencing the variation of their area ratio.

Figure 5 shows the U/P area ratios of spots in the states of maximum umbral areas plotted with black circles. Their distribution exhibits a clear inverse relationship with the maximum area; larger spots have relatively smaller umbrae with respect to the penumbrae. The other diagram, the decay rates versus maximum area, is taken from an earlier paper (Muraközy 2021); the data are plotted with open triangles. Both data sets are averaged over 10 MSH bins of maximum umbral area. The opposite trends of the two diagrams are conspicuous; larger umbrae decay faster than smaller ones, and their areas with respect to their penumbrae are smaller than in small sunspots. This is in agreement with the theoretical result of Rempel & Cheung (2014) that the larger penumbra stabilizes the sunspot, but it contradicts the results of Brandt et al. (1990), Carrasco et al. (2018b), and Hathaway (2013). This dependence is also in contrast to Hoyt & Schatten (1997), who found a linear relationship between the U/P values and the decay rates.

The decay process also exerts an impact on the variation of U/P ratio as is shown in Figure 6. The sample is divided into three groups of sizes as in Figure 4; the data of leading and following parts, as well as the entire groups, are plotted separately, and the decay is represented again in a standard time interval normalized to the lengths of decays starting with the maximum area (at zero ADP). The most striking feature of these diagrams is the definite decrease of the U/P ratio during the decay in the following parts of the sunspot groups (indicated with open circles), which means that in the trailing regions the umbrae disappear more quickly than the penumbrae. In the leading parts the decreasing trend is also present, but with some temporary strengthening. This may be due to the typically larger leading umbrae, which may be more resistant to the disintegrating due to external impacts than those of the trailing part. Anyhow, the overall trend is that the deeper rooted umbrae are more intensively exposed to the decomposing impact of the external processes than the penumbrae close to the surface layers.

The courses of the decays of the leading part and the whole group are similar in each case. As a result of this U/P study, one can conclude that the smaller the sunspot group area, the higher the U/P ratio and the difference between values of the leading and following parts. Moreover, the smaller the sunspot groups, the higher the variation of this ratio during the decay.

4. Summary and Conclusion

During the decay process of sunspot groups, several characteristic variations happen in their internal structures. The results can be summarized as follows.

1. The sunspot group’s decay can be divided into three parts where the leading/following asymmetries vary with different rates (left panel of Figure 2). This asymmetry is almost constant in the first phase of the decay; its ratio

![Figure 5](image-url)  
**Figure 5.** The $a_u/a_p$ value at the time of maximum umbrae averaged over 10 MSH bins as a function of maximum umbral area depicted with black circles. The umbral decay rate (Muraközy 2021) is also averaged over 10 MSH bins as a function of maximum umbral area, plotted with open triangles.

![Figure 6](image-url)  
**Figure 6.** Umbra and penumbra ratios of the whole groups (crosses) and their leading (filled circles) and following (open circles) parts as a function of the umbral ADP. The values of $a_u/a_p$ are averaged over 10% bins of the umbral ADP. 0% marks the maximum umbral area. Top left panel: $A_u > 20$ MSH; top right panel: $20$ MSH $< A_u < 60$ MSH; bottom left panel: $A_u > 60$ MSH.
slightly varies and is preserved from the time of the maximum of the groups. Then, that varies faster during the middle phase of the decay. After this steeper variation, the area asymmetry seems to be stabilized.

2. The variation of the leading–following umbral area asymmetry depends on the sunspot group’s maximum size. It rises earlier in small groups that contain typically small spots that disappear more quickly. The asymmetry variation of the total (U+P) area is less sensitive to the disintegrating impacts; the variation of curves of the penumbrae is more flattened than that of the umbrae (right panel of Figure 2).

3. The leading/following area asymmetry also exhibits hemispheric difference (Figure 3). During the sunspot group’s decay, the area asymmetry index has higher values in the southern hemisphere.

4. The umbra–penumbra ratio at the time of maximum umbra exhibits anticorrelation with the area (Figure 5). The decay rate and the U/P ratio are inversely proportional.

5. The variation of the umbra–penumbra ratio during the decay depends on the maximum area of the group and also on the leading or following positions of the spots (Figure 6). The variation is typically a decrease, which is the strongest in the following parts of small groups, but in the leading parts some temporary strengthenings may occur. The presented processes imply that the umbrae are more exposed to disintegrating effects than the penumbrae, which are only affected by surface velocity fields.

The behavior of the larger groups differs from that of medium and small groups in many ways, e.g., the average area of sunspots within the groups, the U/P ratio, and the variation of the area asymmetry index. The physical conditions affecting them are different. The leading–following area asymmetry changes rapidly, and the following spots vanish earlier, but the ratio between the umbra and penumbra hardly changes mainly in the case of the leading spots. This means that the decay of the larger groups is a smooth process, while the small groups behave more chaotically.

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References

Baranyi, T., Győri, L., & Ludmány, A. 2016, SoPh, 291, 3081
Brandt, P. N., Schmidt, W., & Steinegger, M. 1990, SoPh, 129, 191
Carrasco, V. M. S., García-Romero, J. M., Vaquero, J. M., et al. 2018a, ApJ, 865, 88
Carrasco, V. M. S., Vaquero, J. M., Trigo, R. M., & Gallego, M. C. 2018b, SoPh, 293, 104
Chowdhury, P., Choudhary, D. P., & Gosain, S. 2013, ApJ, 768, 188
Cowling, T. G. 1946, MNRAS, 106, 218
Deng, N., Choudhary, D. P., Tritschler, A., et al. 2007, ApJ, 671, 1013
Gafeira, R., Fonte, C. C., Pais, M. A., & Fernandes, J. 2014, SoPh, 289, 1531
Hagenaar, H. J., & Shine, R. A. 2005, ApJ, 635, 659
Hathaway, D. H. 2013, SoPh, 286, 347
Howard, R. F. 1993, SoPh, 145, 95
Hoyt, D. V., & Schatten, K. H. 1997, The Role of the Sun in Climate Change (Oxford: Oxford Univ. Press)
Javaraiah, J., Baranyi, T., & Ludmány, A. 2014, SoPh, 289, 563
Li, J., & Ulrich, R. K. 2012, ApJ, 758, 115
Martínez Pillet, V., Moreno-Insertis, F., & Vázquez, M. 1993, A&A, 274, 521
McClintock, B. H., & Norton, A. A. 2013, SoPh, 287, 215
Muraközy, J. 2021, ApJ, 908, 133
Muraközy, J.; Baranyi, T., & Ludmány, A. 2014, SoPh, 289, 563
Norton, A. A., Jones, E. H., Linton, M. G., & Leake, J. E. 2017, ApJ, 842, 3
Panja, M., Cameron, R. H., & Solanki, S. K. 2021, ApJ, 907, 102
Petrovay, K., & van Driel-Gesztelyi, L. 1997, SoPh, 176, 249
Piddington, J. H. 1975, Ap&SS, 34, 347
Rempel, M., & Cheung, M. C. M. 2014, ApJ, 785, 90
Schlichenmaier, R., Bello González, N., Rezaei, R., & Waldmann, T. A. 2010, AN, 331, 563