The evolution of flaring and non-flaring active regions

A. Kilcik, V. Yurchyshyn, S. Sahin, V. Sarp, V. Obridko, A. Ozguc, J. P. Rozelot

Monthly Notices of the ROYAL ASTRONOMICAL SOCIETY
MNRAS 477, 293–297 (2018) doi:10.1093/mnras/sty388

The evolution of flaring and non-flaring active regions

A. Kilcik,[1]⋆ V. Yurchyshyn,[2,3]⋆ S. Sahin,[1] V. Sarp,[1] V. Obridko,[4] A. Ozguc[5] and J. P. Rozelot[6]

[1] Akdeniz University Faculty of Science, Department of Space Science and Technologies, 07058 Antalya, Turkey
[2] Big Bear Solar Observatory, New Jersey Institute of Technology, Big Bear City, CA 92314, USA
[3] Korea Astronomy and Space Science Institute, Daejeon 305-348, South Korea
[4] Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation of the Russian Academy of Sciences (IZMIRAN), Troitsk, Moscow, 142190 Russia
[5] Kandilli Observatory and Earthquake Research Institute, Bogazici University, 34684 Istanbul, Turkey
[6] Université de la Côte d'Azur (OCA-CNRS) and 77, Ch. des basses Moulieres, 06130 Grasse, France

Accepted 2018 February 12. Received 2017 November 16; in original form 2017 September 7

ABSTRACT

According to the modified Zurich classification, sunspot groups are classified into seven different classes (A, B, C, D, E, F and H) based on their morphology and evolution. In this classification, classes A and B, which are small groups, describe the beginning of sunspot evolution, while classes D, E and F describe the large and evolved groups. Class C describes the middle phase of sunspot evolution and the class H describes the end of sunspot evolution. Here, we compare the lifetime and temporal evolution of flaring and non-flaring active regions (ARs), and the flaring effect on ARs in these groups in detail for the last two solar cycles (1996 through 2016). Our main findings are as follows: (i) Flaring sunspot groups have longer lifetimes than non-flaring ones. (ii) Most of the class A, B and C flaring ARs rapidly evolve to higher classes, while this is not applicable for non-flaring ARs. More than 50 per cent of the flaring A, B and C groups changed morphologically, while the remaining D, E, F and H groups did not change remarkably after the flare activity. (iii) 75 per cent of all flaring sunspot groups are large and complex. (iv) There is a significant increase in the sunspot group area in classes A, B, C, D and H after flaring activity. In contrast, the sunspot group area of classes E and F decreased. The sunspot counts of classes D, E and F decreased as well, while classes A, B, C and H showed an increase.

Key words: Sun: activity – (Sun:) sunspots – Sun: flares.

1 INTRODUCTION

Solar spots are regions on the solar disc with strong magnetic fields that generally appear in groups called active regions (ARs). Sunspots appear darker than their surroundings because convection is partially suppressed by strong magnetic fields (Priest 2014). They have a characteristic pattern of emergence, evolution and decay. At the onset of their development, they appear as a small group of pores, and their development peaks within 3–10 d, after which they gradually disappear. The size of a sunspot varies in the range 5–50 Mm (Parnell et al. 2009), while their lifetime varies from a fraction of a day to up to 3 months, or even longer. Sunspots tend to emerge within the equatorial belt, also called the active belt, which lies between ±35° heliographic latitude. The latitude of sunspots varies with the solar activity cycle. At the beginning of a cycle, sunspots appear at high latitudes, with occasional spots appearing up to 40–45° off the equator, then drift towards the equator over time (Maunder 1904; Solanki 2003). Typically, the lifetime of a sunspot increases linearly with its maximum size (Gnevyshev 1938; Waldmeier & Bachmann 1955).

Their morphology, evolution, size, presence of the penumbra, complexity, longitudinal extension and interior spot distribution all define the sunspot classification. The first classification was based on the sunspot shape by Cortie (1901). Later, Waldmeier & Bachmann (1955) introduced the Zurich classification schema, which is based on sunspot morphology and evolution. Finally, the Zurich classification was further modified by McIntosh (1990) to include properties of an AR such as the number and development of sunspots within a group and the presence of umbra and penumbra. McIntosh (1990) found that this scheme is better at describing the flare productivity of ARs. The three-parameter classification combines the advantages of evolutionary and magnetic classifications. Its drawback is that the data are hard to interpret. Perhaps that is why many statistical properties have not been studied so far, and

⋆ E-mail: kilcikali@gmail.com, alikilcik@akdeniz.edu.tr (AK); vayur@bbso.njit.edu (VY)

Published by Oxford University Press on behalf of the Royal Astronomical Society

the evolutionary path of a group in the three-dimensional space of these classes has not been elucidated. On the other hand, this classification scheme has become the basis for many forecasting systems, especially in the United States.

Solar flares explosively release large amounts of energy in the form of particles and radiation, varying from radio waves to gamma-rays. The amount of radiant energy depends on the intensity and duration of a flare and can be quantified based on their intensity measured in the hydrogen alpha (6563 Å) spectral line and the soft X-ray (SXR) spectral range (1–8 Å). The hydrogen alpha classification is derived from the size of a flare area and its peak brightness. The SXR classification is a base-10 magnitude system supported by the radiation flux measured by the Geostationary Operational Environmental Satellite (Aschwanden & Freeland 2012). Each higher class of a flare exhibits a peak of SXR emission 10 times greater than the previous one. All solar flares can be separated into five classes: A, B, C, M and X. In this statistical study, we considered only flare events of SXR class C and higher, which could potentially be geoeffective.

Various studies show a well-pronounced relationship between the sunspot group classifications and the solar flare activity (Kleczek 1953; Lee et al. 2012; Eren et al. 2017, and references therein). Kilcik et al. (2011) found that time variations of the large group set that includes classes D, E and F better describe the number of solar flares and coronal mass ejections during a solar cycle than the small one does. Lee et al. (2012) separated sunspot groups into two categories with a large or small area. They further divided these two categories into three sub-groups (decreasing, steady and increasing) according to changes in area. They found that flaring increases noticeably with increased sunspot group area. Recently, Eren et al. (2017) analysed each modified Zurich class, focusing on their flare production potential, and found that about 80 per cent of flares are produced by large or complex groups.

McCloskey, Gallagher & Bloomfield (2016) investigated variations in sunspot group classification and flaring rates from 1988 to 1996 and found an increase in the flaring rates for upward evolving ARs (from small to large, and simple to complex). Kilcik et al. (2018) analysed temporal and periodic variations of flaring and non-flaring ARs, and found that their behaviour differed during the last two solar cycles. In this study, we further investigate the lifetime evolution and morphological changes in sunspot groups based on the first parameter of the modified Zurich classes (A, B, C, D, E, F and H), separately for flaring and non-flaring ARs.

Here we focus on the observed morphological variations, measured using the Zurich class 1 d after flaring activity. The article is structured as follows. In Section 2, we describe the data sets and the methods used. In Section 3, we present our analysis and results. A discussion and conclusion are given in Section 4.

2 DATA AND METHODS

The data used in this study were taken from the Space Weather Prediction Center of the National Oceanographic and Atmospheric Administration (NOAA) for the time period from 1996 January through 2016 August. We separated the data into two categories based on their flaring activity. The sunspot groups having at least one flaring event during their lifetime were counted as flaring ARs and the ones with no flaring event during their lifetime belong to the non-flaring category. Also note that we considered ARs only within $\pm 70^{\circ}$ of the heliographic longitude to eliminate the effect of projection on the sunspot classification, spot counts and group area measurements. According to this criterion, in total 4529 ARs were analysed: 1754 of them were flaring ARs and 2775 belonged to the non-flaring set. As a first step, we compared their lifetimes (Section 3.1). Secondly, we analysed the temporal evolution of each class of ARs and compared it to their flare production (Section 3.2). Finally, we considered the evolution of the Zurich class after a flaring event (Section 3.2).

Table 1. Average lifetimes of flaring and non-flaring ARs according to their modified Zurich classes.

Modified Zurich class	Number of flaring ARs	Average lifetime (d), flaring ARs	Number of non-flaring ARs	Average lifetime (d), non-flaring ARs
A	86	7.55	500	3.33
B	241	6.99	809	3.59
C	464	8.19	645	4.70
D	505	8.48	301	5.15
E	121	10.55	9	9.56
F	27	10.30	1	10.00
H	310	9.80	510	7.78

3 ANALYSIS AND RESULTS

3.1 Lifetime of flaring and non-flaring ARs

As we mentioned above, the lifetime of sunspots and sunspot groups varies from a fraction of a day to a few months. Note that here we used the NOAA AR number as a reference. When an AR first appears, it is assigned a NOAA number, then when it reappears during the next rotation of the Sun, this number changes. Therefore we limited the lifetime of ARs with maximum 13 d. In general, flaring ARs in all classes exhibit longer lifetimes than the non-flaring ones. ARs of classes A, B, C and D live nearly twice as long as non-flaring ARs, while the lifetimes of E and F groups are comparable and the longest for both flaring and non-flaring sets. The average lifetimes of flaring and non-flaring ARs are given in Table 1.

3.2 Evolution of flaring and non-flaring ARs

We analysed all modified Zurich classes during their lifetime to reveal their evolution pattern (see Figs 1 and 2).

Each plot in these figures shows the long-term evolution of a Zurich class during the 11-d period after the first appearance on the visible solar disc. For example, on day 0 (not shown in the plot), some ARs were of class A. On day 1, some of the class A ARs were re-classified as class B, C, D or H, while some fraction remained in class A (upper left plot of Fig. 1). For this group of initially small flaring ARs, as time passes, more and more of them evolve upward towards class D (left column). If a flaring AR starts as class B or C, then it will most probably evolve to class C or D by the next day and these will most likely be their peak classes. Non-flaring A, B and C groups do not exhibit such a rapid shift in morphology and the majority of them remain in their initial class with a small fraction gradually migrating towards higher classes as time passes (left column, Fig. 1). In both sets of ARs, class H shows a significant downward migration towards simpler magnetic classes.

According to Fig. 2, flaring groups of class D, E or F do not change classification drastically during their evolution. Instead, there is a slow upward and downward migration from the original class combined with a gradual disappearance. When we look at the evolution

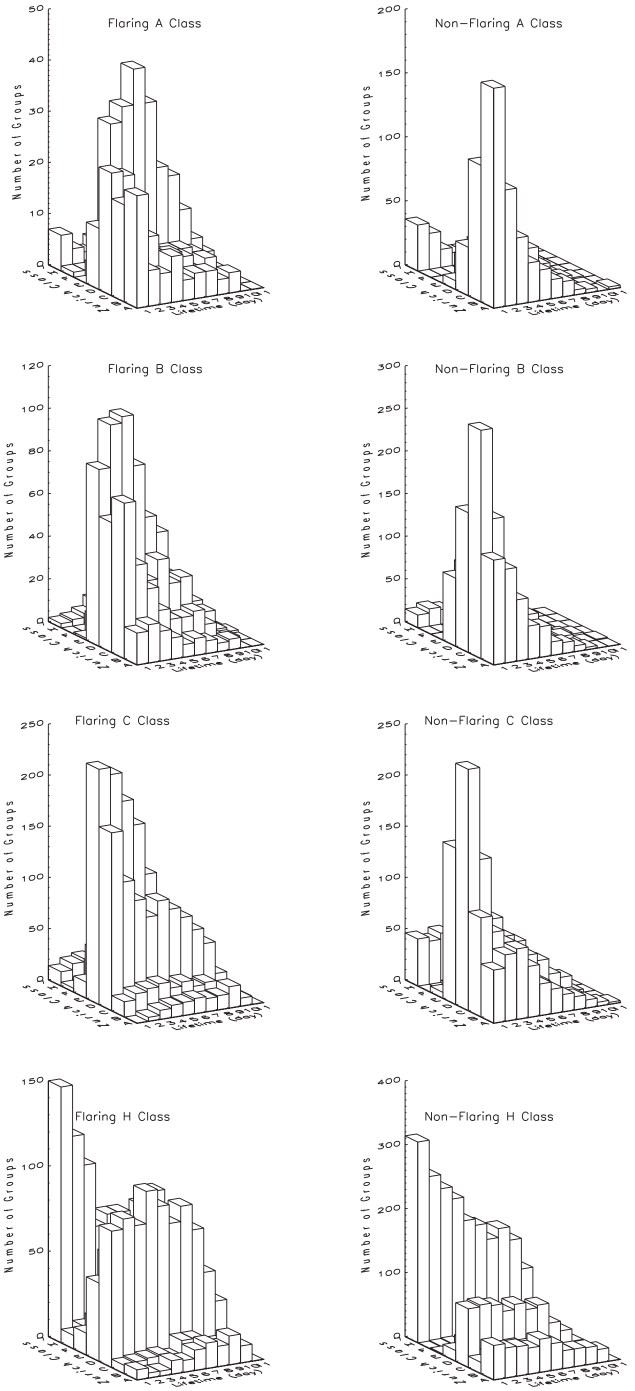

Figure 1. Evolution of Zurich class during the lifetime of ARs, plotted separately for flaring (left) and non-flaring (right) ARs for classes A, B, C and H of small ARs. See details in the text.

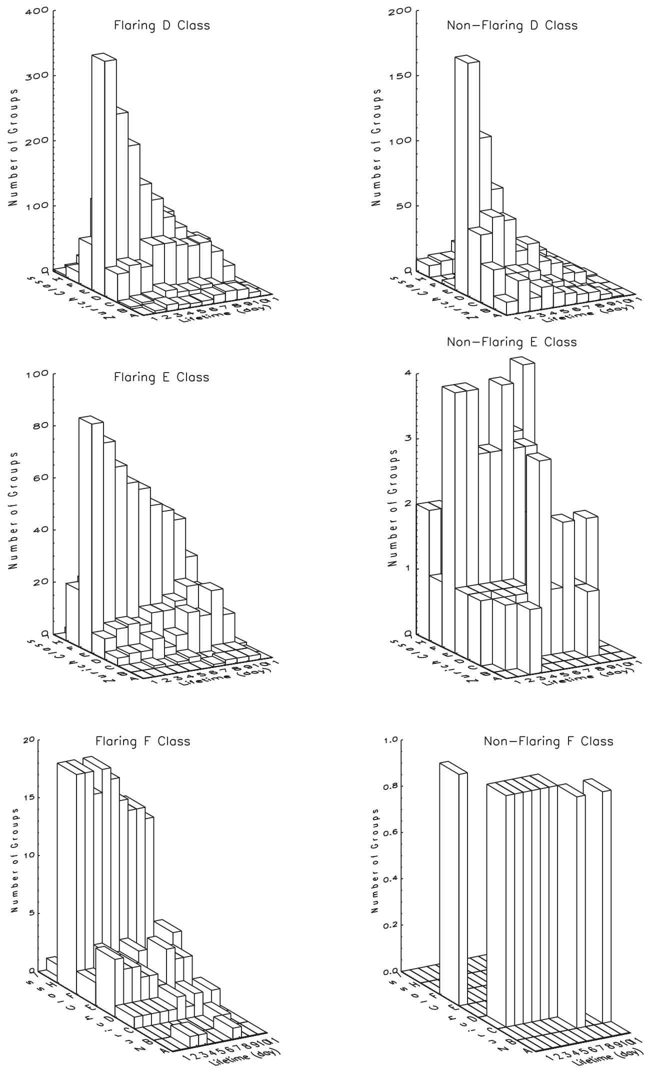

Figure 2. Evolution of Zurich class during the lifetime of ARs, plotted separately for flaring (left) and non-flaring (right) ARs for classes D, E and F of large ARs. See details in the text.

of non-flaring ARs (Figs 1 and 2, right), they mainly remain in the same classification during their lifetime. Note that their lifetimes are shorter than those of flaring ARs.

3.3 Flaring effect on sunspot groups

To investigate how flaring affects the class evolution of ARs, we considered all flaring episodes (each episode may include one or more flares) in all flaring ARs and followed the evolution of their class. Altogether, 4312 flaring episodes occurred in all classes of sunspot groups (Fig. 3).

For flaring ARs, the maximum in the distribution of flares occurs for class D. In McIntosh (1990), the maximum of the distribution is for groups of class F. This difference is probably because McIntosh (1990) took into account only strong flares of classes M and X. In our figure, all flares of class C_0 and higher were taken into account. On the other hand, this may be a specific trait of low activity in cycles 23 and 24.

We recorded changes in the modified Zurich class, average sunspot counts (SSCs) and sunspot areas (SSAs) that occurred between the flaring day and the day after the flare event (Table 2). The table shows the percentage of ARs of a given initial class (leftmost column) that changed class. For example, there were 53 flaring events in class A groups and there was no classification change in 36 per cent of these ARs, while 64 per cent of them changed (18.9 per cent evolved to B, 22.6 per cent to C, 18.9 per cent to D and 3.8 per cent to H). The general tendency seen in this table is that most of the class A and B groups rapidly evolved to higher classes (C and D). Starting from class C, the tendency changes and the

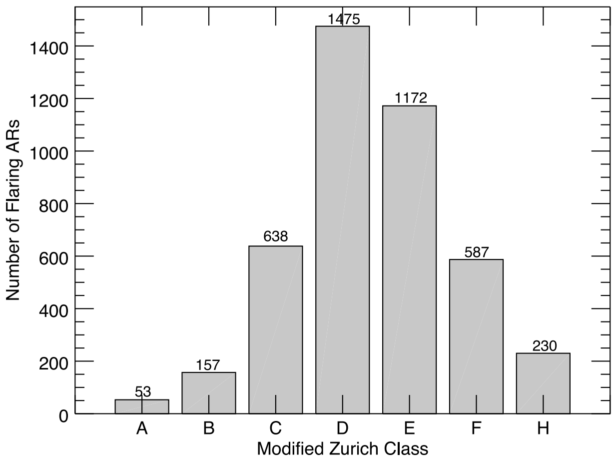

Figure 3. Distribution of flaring ARs according to their modified Zurich class.

majority of the groups remain in their original class after a flaring event. For SSCs and SSAs, all but class F showed a similar trend. The SSC and SSA magnitude increases with ARs evolving upward to a higher class. These two parameters rapidly decrease when the transition to class H occurs.

4 CONCLUSIONS AND DISCUSSIONS

We investigated the lifetime and morphological evolution of sunspot groups observed during solar cycles 23 and 24 (from 1996 to 2016) in terms of their modified Zurich classification. We also investigated the effect of flaring on sunspot group evolution. Our main findings are as follows:

1. Flaring sunspot groups live longer than non-flaring ones. In all cases, the lifetime of class H ARs is longer than that of classes A, B, C and D.

2. Most of the class A, B and C flaring ARs rapidly evolve to higher classes, but this is not applicable for non-flaring ARs. More than 50 per cent of flaring A, B and C groups changed morphologically, while the remaining D, E, F and H groups did not change remarkably after flare activity.

3. 75 per cent of all flaring sunspot groups are large and complex (modified Zurich classes D, E and F).

4. There is a significant increase in the sunspot group area in classes A, B, C, D and H. In contrast, the sunspot group area of classes E and F decreased after flaring activity. The sunspot counts of D, E and F groups decrease as well, while the A, B, C and H groups showed an increase.

For very energetic flares (classes M and X) of sunspot groups observed from 1996 January to 2003 June, Ternullo et al. (2006) analysed the heliographic coordinate, sunspot number, sunspot area, Zurich class, etc. They found that flaring groups have longer lifetimes than non-flaring ones. We used here a flare threshold, the X-ray class C, and arrived at a similar conclusion that flare-producing ARs live longer.

McCloskey et al. (2016) concluded that the flaring rate increases when ARs observed between 1988 and 1996 evolve to a higher Zurich class and the flaring rate decreases for the downward evolution. Our analysis based on solar cycles 23 and 24 (1996 through 2016) confirms their results but only for small sunspot groups. When we consider the evolution of large sunspot groups (classes D, E and F), the upward and downward evolutions are balanced. Also, most of these sunspot groups did not change their classification during the 24 h following flare occurrence.

Eren et al. (2017) calculated the flare production potential for each modified Zurich class separately using similar data as we

Table 2. Temporal evolution between the flaring day and the day after flaring for all classes of flaring ARs. SSC and SSA in the leftmost column describe the average variation of sunspot counts and area, respectively.

Class (No. of cases)	A	B	C	D	E	F	H
A (53)	35.8 per cent	18.9 per cent	22.6 per cent	18.8 per cent	0 per cent	0 per cent	3.8 per cent
SSC	0.3	2.3	3.5	7.5	–	–	0.0
SSA	0.3	4.0	28.3	44.0	–	–	5
B (157)	11.5 per cent	31.1 per cent	26.1 per cent	25.5 per cent	1.3 per cent	0 per cent	2.5 per cent
SSC	−2.4	0.7	2.3	7.1	7.0	–	−0.8
SSA	−5.3	0.4	30.5	66.0	130.0	–	10
C (638)	2.4 per cent	3.9 per cent	48.4 per cent	33.1 per cent	3.3 per cent	0.5 per cent	8.5 per cent
SSC	−3.2	−1.5	−0.1	3.7	4.0	5.3	−2.6
SSA	−19.3	−21.2	−1.9	38.1	65.7	43.3	−10.1
D (1475)	0.1 per cent	1.1 per cent	10.8 per cent	73.0 per cent	12.9 per cent	0.9 per cent	1.1 per cent
SSC	−10	−1.6	−1.7	1.4	4.6	9.14	−4.9
SSA	−85.0	−25.0	−21.1	23.3	66.8	172.9	−38.1
E (1172)	0 per cent	0 per cent	2.9 per cent	7.9 per cent	80.4 per cent	8.4 per cent	0.3 per cent
SSC	–	–	−5.4	−2.1	0.6	4.3	−5.5
SSA	–	–	−44.4	−14.8	7.0	50.8	−33.8
F (587)	0 per cent	0 per cent	1.4 per cent	1.4 per cent	10.1 per cent	87.1 per cent	0.2 per cent
SSC	–	–	−0.1	−4.6	−0.3	−0.9	−5
SSA	–	–	−35.0	3.8	−27.8	−12	−90.0
H (230)	4.8 per cent	3.0 per cent	25.2 per cent	11.7 per cent	3.5 per cent	1.3 per cent	50.4 per cent
SSC	0.0	−0.3	2.6	5.4	7.3	14.0	0.0
SSA	−12.7	−10.0	2.8	57.4	18.8	373.3	−0.8

used. Their data cover the period between 1996 and 2014, while the data that we used in this study cover the period between 1996 and 2016. They found that the flare production potential of large sunspot groups (D, E and F) is about eight times higher than for the other classes (A, B, C and H). They also found that about 80 per cent of all flares occur in the large and complex sunspot groups. In this study, we confirmed their results by using sunspot group numbers and further found that 75 per cent of all flaring sunspot groups are large and complex.

Earlier, Kilcik et al. (2011, 2014) concluded that the number of flares increases when the size and complexity of a sunspot group increases. In this study, we showed the effects of the size and complexity of sunspot groups and flares. As shown in Table 2, each sunspot group evolves differently after the occurrence of flares. Moreover, each sunspot group has different variations of sunspot number and sunspot area. From these results, it can be inferred that sunspot groups show different temporal variations. Large sunspot groups (D, E and F) decrease according to the temporal evolution of average variations of sunspot number while other sunspot groups (A, B, C and H) show an increase. There is a significant increase in the sunspot group area of groups A, B, C, D and H. In contrast, the sunspot group areas of E and F groups decrease after flaring activity.

The occurrence rate of solar flares and the sunspot classification with sunspot number and area changes were studied by Lee et al. (2012) from 1996 January to 2010 December. First, they divided sunspot groups into two categories as small and large, then these two categories were divided into three sub-categories (decreasing, steady and increasing) according to the change of area. They found that 11 sunspot classes in the McIntosh sunspot group classification schema produced most of the observed flares. Our results confirm this using sunspot group number and area and that 75 per cent of the flaring sunspot groups are large or complex (D, E and F). It can also be inferred from our results that small sunspot groups are in the increasing sub-group while large sunspots are in the steady or decreasing sub-groups.

Finally, according to the data analysed, solar flares occur in developing ARs and flaring ceases or significantly subsides when development is arrested. This is consistent with the idea that new emerging flux is needed (or helicity injection) to fuel the energy release that occurs in the form of flares and coronal mass ejection. For a large flare, the emergence of a sufficiently large flux (>1013 Wb) and large ascent rate >109 Wb s^{-1} (Ishkov 1998) are required. This rapid upward evolution of flaring ARs is in accord with earlier findings that the ARs prone to produce X-class flares emerge with a very steep (>2) magnetic power spectrum (Abramenko 2005; Abramenko & Yurchyshyn 2010). This means that flaring ARs are born bad and destined to produce big flares at the emergence stage (Abramenko 2005; Abramenko & Yurchyshyn 2010). A practical application of this analysis is that it may help us to predict which newly born ARs may develop into flare-producing ARs. The class A and B sunspot groups that display flaring activity have higher chances of developing into mature class D, E and F structures capable of producing strong eruption and geomagnetic events.

ACKNOWLEDGEMENTS

All data for flaring and non-flaring ARs used in this study were taken from the Space Weather Prediction Center. This study was supported by the Scientific and Technical Council of Turkey by project 115F031. VYu acknowledges support from the Air Force Office of Scientific Research (grant FA9550-15-1-0322), the National Science Foundation (grant AST-1614457) and the Korea Astronomy and Space Science Institute. We thank the International Space Science Institute in Bern for enabling interesting discussions. JPR acknowledges the International Space Science Institute in Bern, Switzerland, where he is regularly invited as a visiting scientist.

REFERENCES

Abramenko V., 2005, ApJ, 629, 1141
Abramenko V., Yurchyshyn V., 2010, ApJ, 720, 717
Aschwanden M., Freeland S., 2012, ApJ, 754, 112
Cortie A. L., 1901, ApJ, 13, 260
Eren S., Kilcik A., Atay T., Miteva R., Yurchyshyn V., Rozelot J., Ozguc A., 2017, MNRAS, 465, 68
Gnevyshev M., 1938, Mitteilungen der Nikolai-Hauptsternwarte zu Pulkowo., 16, B36
Ishkov V., 1998, Bull. Russian Acad. Sci. Phys., 62, 1835
Kilcik A., Yurchyshyn V. B., Abramenko V., Goode P. R., Ozguc A., Rozelot J. P., Cao W., 2011, ApJ, 731, 30
Kilcik A., Yurchyshyn V. B., Ozguc A., Rozelot J. P., 2014, ApJ, 794, L2
Kilcik A., Yurchyshyn V., Donmez B., Obridko V.N., Ozguc A., Rozelot J.P., 2018, Sol. Phys., 293, 63
Kleczek J., 1953, Bull. Astron. Inst. Czechoslovakia, 4, 9
Lee K., Moon Y., Lee J., Lee K., Na H., 2012, Sol. Phys., 281, 639
Maunder E., 1904, MNRAS, 64, 747
McCloskey A. E., Gallagher P. T., Bloomfield D. S., 2016, Sol. Phys., 291, 1711
McIntosh P., 1990, Sol. Phys., 125, 251
Parnell C. E., DeForest C. E., Hagenaar H. J., Johnston B. A., Lamb D. A., Welsch B. T., 2009, ApJ, 698, 75
Priest E., 2014, Magnetohydrodynamics of the Sun, 2 edn. Cambridge University Press, New York
Solanki S. K., 2003, A&AR, 11, 153
Ternullo M., Contarino L., Romano P., Zuccarello F., 2006, Astron. Nachrichten, 327, 36
Waldmeier M., Bachmann H., 1955, Z. Astrophys., 38, 125

This paper has been typeset from a TEX/LATEX file prepared by the author.