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Flow patterns around old sunspots and flare activity

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Abstract. New magnetic flux emerges significantly more probably in already existing solar active regions. Based on the the Debrecen Observatory photographic observations, several active regions are collected, where at least one large, X-class flare was recorded, and emergence of new activity, birth and quick motion of new umbrae was observed in the vicinity of old spots, the new activity emerged in the center of the old active region.

Newly emerging magnetic flux in older sunspot groups can be distinguished by its quicker and generally westward proper motions. Umbrae of the new activity do not coalesce with older umbrae of the same polarity, but both elastic and inelastic collisions between them can be observed. Spots of the emerging new activity can flow around old unipolar spots (presumably shallower structures, "ω-loops") westward, like a hydrodynamic flow around a cylinder, forming a wake behind it. Collision of different polarities in the wake can lead to large flares. The presence of old spots disturbs the normal emergence of the new activity, so motions of the new spots are distorted by the flow, the new emerging "Ω-loop" can be stuck between the umbrae of the old, tight dipole, the orientation of the new dipole can be distorted by as much as 180°. The general direction of the flow around the old spots seems to depend on the latitude, the angle between the motion axis and the E-W direction grows with the latitude.

The intensive flare activity seems to be connected strongly with the newly emerging magnetic flux; interacting of differently oriented dipoles and the difference of the orientation of the emerging new dipole from the ordinary Hale-Nicholson orientation is also significant. Simply large gradients of magnetic fields (δ-configuration) are not enough, dynamical processes (emergence of new flux, shearing or colliding motions of umbrae of different magnetic polarity) must also be present for large flares.

Key words: Sun: activity – Sun: flares – sunspots

1. Introduction

Although sunspots have been observed systematically already since Galileo, their understanding begun only in this century, when Hale discovered their strong magnetic fields. With the development of magnetohydrodynamics and study of magnetic flux tube behavior it became possible to explain the temperature deficit in the umbra, the structure of the isolated regular sunspot and the distorted convection in the penumbra (see reviews by Thomas & Weiss 1992; Zwaan 1992; Jahn 1992). Existing dynamo theories explain the emergence of originally horizontal fluxtubes stored just below the convective zone due to instabilities resulting from magnetic buoyancy (Parker 1996). The general picture is thus more or less clear, but the real sunspots are usually more complex, as often neither the sunspots, nor the sunspot groups are isolated. It is well known that new magnetic flux (new sunspots) more often emerge inside already existing spotgroups. The observed excess ranges from about ten times (Liggett & Zirin 1985) to 25 times (Harvey & Zwaan 1983). This fact is connected with the tendency of formation of active regions in clusters, "complexes of activity" (Bumba & Howard 1965; Gaizauskas et al. 1983; Gaizauskas 1993), where impulses of magnetic flux emerge during a prolonged period of time, creating several active regions. The interaction of old and new activity may shed light on the structure and dynamics of emerging fluxtubes in the convective zone (Tanaka 1991). These layers are inaccessible for direct observation, only recently helioseismological observations gave some hints on the depth structure of the active regions (Kosovichev 1996a; Lindsey et al. 1996).

In the Debrecen Heliophysical Observatory the proper motions of sunspot umbrae are studied since 1969, based on the systematic full-disk observations of the Observatory. In studying development and motion in sunspot groups, several examples were found, where the trajectories of the individual umbrae resemble simple hydrodynamical flow patterns. Some of these are described in this paper. The structure of the paper is as follows: in Sect. 2. the observational material and the reduction procedure is outlined, in Sect. 3. the general characteristics of the studied active are described, in Sect. 4. the observed flow patterns discussed and finally in Sect. 5. the conlusions are drawn.

2. Observational material

Photographic observations were taken from the plate collection of the Debrecen Observatory. The telescopes used are photoheliographs of 13 and 15 cm objective diameter, respectively, in

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Debrecen and the Observatory's Gyula Observing Station (100 km to the south from Debrecen). In both photoheliographs the primary focal length is approx. 2 meters, the primary solar image is enlarged five times to get a 10 cm diameter image. The whole solar disk is photographed on 14×14 cm high contrast phototechnical film (Agfa-Gevaert P911p) on polyester base for high dimensional stability. A metal-interference filter restricts the spectral content of the incoming light to a 100 Å wide band centered at 5500 Å. Exposures are made at the visually selected moments of best seeing. One series of observations consists of three images, one single and two double exposures on both side of the column (German mounting). The single exposure gives an undisturbed image of the Sun, in double exposures the clock drive is stopped immediately after the first exposure, and the image of the Sun is allowed to drift for approximately 100 seconds, when the second exposure is made. The intersection points of the limbs of the two solar images (after accounting for the meridian convergence due to projection, declination change of the Sun, differential terrestrial atmospheric refraction and plate tilt) give the true North-South direction, so the the position angle error of the crosshairs, placed at the prime focus, can be determined. Certain instrumental errors (e.g. plate tilt, and some components of the position angle error, due to imperfect telescope axis orientation) change sign when observing on different sides of the column, so they can be determined and corrected in coordinate measurements. The frequency of observations, besides the weather, depends on the solar activity and in the last years on the quantity of the available photomaterial, but at least one triplet is made every day.

Rectangular coordinates on the photographs were measured with an accuracy of 0.01 mm with a ZEISS ASCORECORD 3DP coordinate measuring machine connected to an IBM compatible PC for digital recording. The reduction software (Kálmán 1980) takes into account the distortion of the enlarging lens system in the heliograph, the tilt of the plate normal to the optical axis and differential atmospheric refraction. All long-lived umbrae which could be unambiguously identified and followed for at least two days were measured, although not all of them are shown on the figures to avoid crowding but to show the general tendency of the motions. Two of the sunspot groups studied had a fairly high latitude, where the effects of the differential solar rotation are noticeable, therefore a correction was made for all measurements according to Newton & Nunn (1951). The individual measurements were averaged and fitted with cubic splines to construct the trajectories of the selected umbrae. As in the present case the motion of new activity was studied in interaction with old spots, the heliographic (Carrington) coordinates were transformed into relative ones with respect to the old spot in the group, which was either stationary or moved very slowly (10-20 m s^{-1})in the Carrington system corrected for differential rotation. (Exception is AR 6659, where a regular, but steadily and evenly moving fragment of the old umbra is chosen as the origin.)

The coordinates of every identified umbra were measured on every usable plate, but for study of the morphological evolution in the sunspot groups on the best quality image of every day the umbral and penumbral contours were also measured (1000–1500 points) to make drawings in corrected Carrington coordinates. Some of these drawings serve as backgrounds for the motion trajectory images.

The repeatability of the measurements is 0.01-0.02 heliographic degrees, however the overall accuracy of one measurement is not better than 0.2-0.3 degrees, mainly due to the atmospheric seeing and to a lesser extent to various instrumental errors. The averaging of several measurements improves the accuracy of the averaged trajectory to 0.05 degrees.

Flare activity of the active regions was taken from SGD (Solar–Geophysical Data, NOAA, Boulder, CO, USA), Comprehensive Reports lists, magnetic polarities from Kitt Peak National Observatory magnetograms (from SGD or KPNO Internet archives) and from NASA Marshall Space Flight Center vector magnetograms (courtesy M. J. Hagyard).

3. General characteristics of the active regions

In the last years motions in several spotgroups on various stages of their evolution were studied in the Debrecen Observatory, mainly complex ones, but not all of them showed large activity (see e.g. Bumba, Klvaňa & Kálmán 1995). Here those active regions are collected, where at least one large, X-class flare was recorded, and emergence of new activity, birth and quick motion of new umbrae was observed in the vicinity of old spots in already existing active regions.

3.1. NOAA 6555 (1991 March 17–31)

The detailed description of the evolution and motions, also the structure of the vector magnetic field in this active region (AR) was published by Fontenla et al. (1995). Its latitude was -25°. The dominant feature was an old, large f-polarity multiple umbra in the eastern (following) part of the region, the origin of the coordinate system. There were already mature umbrae of both polarities in the common penumbra to the west of the old umbra, and on March 21 a new, north–south oriented dipole emerged just to the east, also in the common penumbra, moving westward, as the other young umbrae. The flow pattern of the new umbrae (Fig. 1) around the old one is conspicious (as was remarked by Fontenla et al., 1995), and this led to the search for examples of similar motions. The X-class flares occurred partly at the confluence of the flow behind of the old umbra, where umbrae of different polarity collided (March 22, X9.1), partly on the eastern side, where the p-polarity of the newly emerged dipole moved past of the old f-polarity umbra, creating collision and shear (March 25, X5.3; March 26, X4.7). Detailed description of the evolution of the magnetic shear in connection with flares was published by Ambastha, Hagyard & West (1993).

This complex group was relatively short-lived, like all sunspot groups in this sample.

Two rotations earlier no spots were seen here, one rotation earlier a complex spotgroup (AR 6509) was observed, with large f-polarity umbrae. The next rotation after the here studied one,

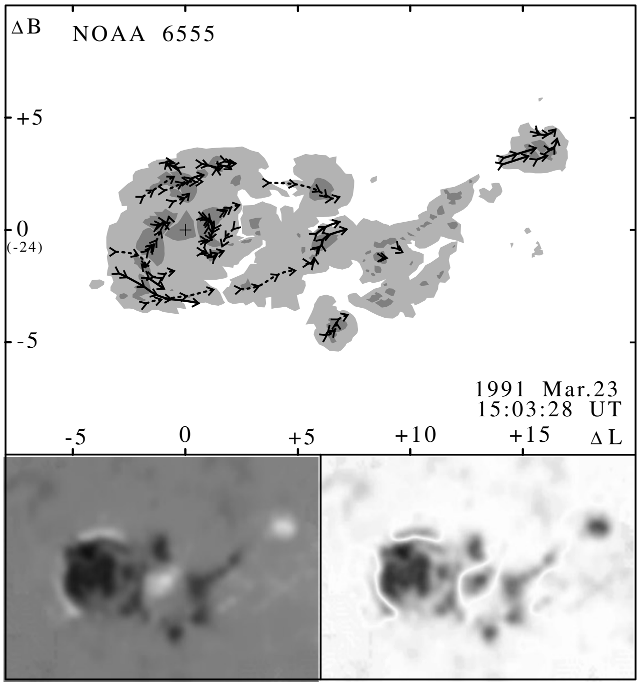

Fig. 1. Trajectories of umbrae in AR 6555 relative to the central old, stable f-polarity umbra, superposed on a drawing in Carrington coordinates (light gray – penumbra, dark gray – umbra). Arrowheads on the trajectories represent position and direction at 12:00 UT every day, full line: p-polarity, dashed line – f-polarity. Approximate latitude of the old spot (coordinate origin) is indicated in parentheses. Lower left: MSFC longitudinal magnetogram, white-preceding, black - following polarity. Lower right: Absolute value of the longitudinal magnetic field, to accentuate polarity inversion lines. The area shown is the same on all three panels of the figure.

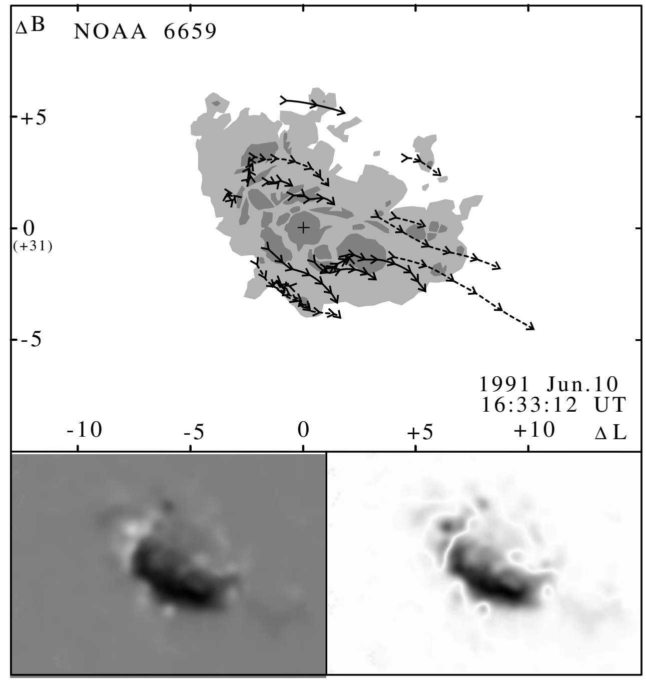

Fig. 2. Trajectories of umbrae in AR 6659 relative to the central p-polarity umbra, which in this case moved with a steady $\sim$100 m s^{-1} velocity in the Carrington system corrected for differential rotation. Notations and layout as in Fig. 1, but as this group was on the northern hemisphere, in the longitudinal magnetogram (MSFC) preceding polarity is black and following is white

only a very dispersed f-polarity background field area remained, with short-lived pores.

3.2. NOAA 6659 (1991 June 3–16)

This high-latitude (+31°) sunspot group set the current record of the energetic flare production with six X10+ flares during its visibility from the Earth and another four on the invisible hemisphere, observed by the Ulysses spacecraft (Kane et al., 1996). Its evolution and proper motions (in Carrington coordinates) were described by Bumba et al. (1993), chromospheric activity and magnetic evolution by Schmieder et al. (1994), white-light flares by Sakurai et al. (1992) and Zhu & Shen (1992), the vector magnetic field characteristics by Zirin & Wang (1993) and Zhang (1996). The group was dominated by a huge p-polarity multiple umbra, with a middle-sized f-polarity umbra touching it on the northeastern side, and other smaller f-polarity umbrae around, all in a common penumbra, except some small spots. It was a typical island-δ configuration (Zirin & Liggett 1987). New magnetic flux emerged just in the middle of the group, on the polarity dividing line of the old dipole. The evolution of the new flux was unusual (Fig. 2): the orientation and motion of the new dipole was reversed: f-polarity streamed westward and p-polarity eastward (Bumba et al. 1983). All the large X-class flares were connected with the polarity inversion line between the old f-polarity umbra and the newly emerging p-polarity umbrae in the middle. In this active region all the prerequisites of large flare activity are present: inverted dipole, emerging flux, collision of different polarities and shear motion; no wonder that there were several really big flares.

The history of the region began two rotations earlier than the 1991 June one. In its first rotation as AR 6580 (April 7-19, it was born on the invisible hemisphere) it was a small group with an unusual north-south oriented axis. Its flare activity was moderate, occurring mainly after central meridian passage, when growth of the p-polarity (southern) part began. In the next rotation (AR 6619, May 5-18) the area of the group was significantly larger, the overall configuration was strikingly similar to AR 6659 in the next, June rotation, an island-δ, with a large p- and a smaller f-polarity umbra, almost touching each other in a common penumbra, the tilt of the axis of the group to the E-W direction was about 60°. Nevertheless the flare activity was even smaller than in the previous rotation. After the June rotation as AR 6659 with exceptional activity, described here, in the next rotation only several small spots were seen in this area, and two rotations later no trace of activity was visible even in the background magnetic fields. Such quick disintegration of a

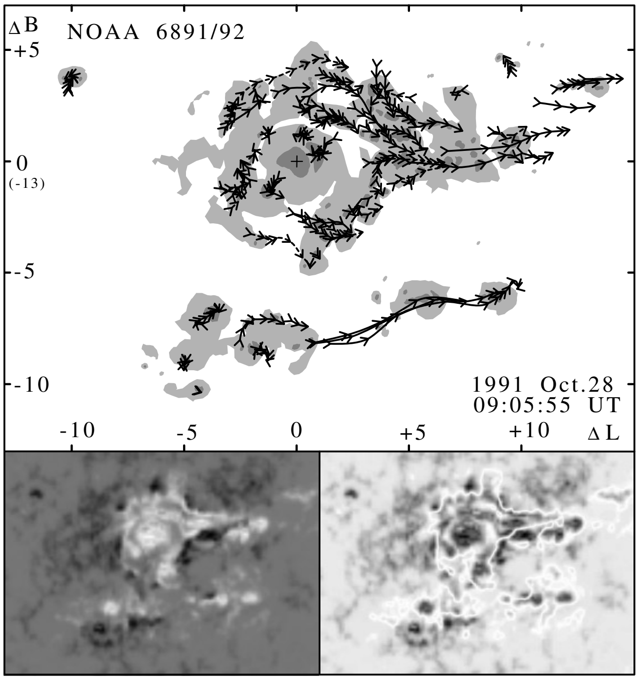

Fig. 3. Trajectories of umbrae in AR 6891 relative to the larger part of the central stable old p-polarity double umbra. Notations and layout as in Fig. 1, longitudinal magnetogram from KPNO Internet archives.

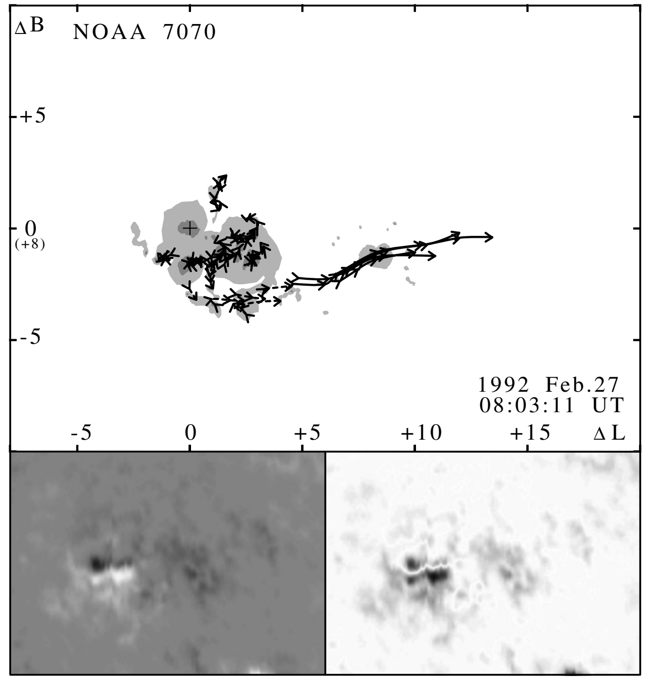

Fig. 4. Trajectories of umbrae in AR 7070 relative to the eastern stable p-polarity umbra. Notations and layout as in Fig. 1. This group was again on the northern hemisphere, so in the longitudinal magnetogram (KPNO) preceding polarity is black and following is white.

superactive region was observed e.g. for the 1972 August region also (Bumba 1980).

3.3. NOAA 6891 (1991 Oct. 23–Nov. 2)

This unusual active region at -13° latitude was part of a long-lived complex of activity, whose evolution was described by Bumba et al. (1996). In this complex there were several spotgroups, the predecessor of AR 6891 was born on the disk two rotations earlier. In the previous rotation it was an elongated group (AR 6850), with δ-configuration in its leading part. In spite of this it produced no larger flares, as f-polarity in the leading part of the group submerged as it was squeezed between the old, leading p-polarity large double umbra and the newly emerging p-polarity umbrae (Bumba, Klvaňa & Kálmán 1995). Such "in situ" disappearence of δ sunspots was described by Wang (1992), but in that case roughly equal opposite magnetic polarities cancelled each other, whereas in AR 6850 only the f-polarity disappeared between an old, stable and a young, growing p-polarity. Probably the submerged f-part disturbed the subsurface structure of the group, which led to the complexity and activity in the next rotation, studied here.

In this rotation the long-lived p-polarity double umbra forms a stable, round spot, with a newer, also p-polarity umbra, also from the previous rotation, attached to it from the southeast. New activity, new spots of both polarities emerge around this spot, and flow to the west, like in the case of AR 6555 (Fig. 3). The magnetic structure is very complex, Wang & Wang (1996) find 71 singular points in a magnetogram, not covering the whole region. In this spotgroup there were 5 X-class flares, two of them white-light ones (Hudson et al. 1992; Liu et al. 1996). These occurred again at the confluence of different polarities in the wake behind the stable old spot, where emerging new f-polarity collided with the p-polarity spots of the northern stream. Interesting to note, that the bright patches of the continuum emission were situated in places of local minima of the longitudinal magnetic fields (see magnetogram in Liu et al., 1996). After this activity the large spots dispersed and only small, insignificant spotgroups appeared in this area of the solar surface in the following rotations (Bumba et al. 1996).

3.4. NOAA 7070 (1992 Feb. 22–March 4)

This low-latitude (+8°), medium-sized δ-group at its appearence at the eastern limb (February 22) had a large roundish penumbra with two east-west rows of umbrae in it, the umbrae of the northern row had p-polarity, the others f-polarity, so it was a north-south oriented irregular dipole (also an island-δ). On February 23-24 new magnetic flux began to emerge in the vicinity of the old complex spot, p-polarity small umbrae near to the western boundary of the large penumbra, f-polarity pores to the south of it. A 2B/M4.9 flare erupted on Feb. 24 synchronously with this evolution. The new p-polarity spots streamed quickly (150-250 m s^{-1}) forward (westward), so did the f-polarity new ones also. The chain of the new pores turned northward under the middle of the large penumbra, intersecting it between the easternmost north-south oriented dipole and the rest (Fig. 4). On Feb. 27

new pores of both polarities appear also to the north of the large penumbra, at the continuation of the chain of pores across the old spot. The large 2B/X3.3 flare occurs this time (Feb. 27), it began at the intersection of the line of pores with the large penumbra (see Brekke 1996), its ribbons covered the umbrae of the easternmost large old dipole, probably this was the cause of the large X-ray flux. After this large flare the new spots quickly faded out and the old umbrae also began to decrease.

The motion of the new umbrae in the western part of the chain shows the usual westward flow of new activity, p- and f-polarity umbrae both move in this direction. As regards the other end of the chain, the emerging fluxtube seems to be entangled in the old multiple-umbra δ-spot; the eastern part of the chain of new spots turns to the north, and emerges on the nothern side of the large penumbra too. The small umbrae move on well-defined streamlines, one frequently following the other on the same trajectory. In the southern part it is visible (from the trajectories) as several new pores are dragged along with the westward flow.

The history of this active region is also short: it developed on the southern boundary of a giant cell of p-polarity background magnetic field. Two rotations earlier this place of the solar surface was empty. One rotation earlier there were two small active regions, NOAA 7030 and 7037, the leader spot of 7030 survived to be included in AR 7070. The spotgroup reached its maximum activity in the rotation studied here as AR 7070, a compact δ-configuration, with new flux emerging inside and in the immediate vicinity, culminating in a large X-class flare. After this flare the new spots disappeared and the old ones also began to decay. In the next rotation only intermittent small pores appeared, and this short-lived complex of activity ceased to exist to the following rotation.

4. Discussion

The observed facts of sunspot group evolution and morphology are well known: The long axis of the groups is (almost) parallel to the solar equator, the preceding spots are nearer, and the angle between the equator and the axis of the group increases with increasing latitude (Joy's law: Joy 1919; Brunner 1930; Howard 1996). In typical regular simple bipolar groups the p-polarity spots are more compact and long-lived than the f-polarity ones. After emergence the p-polarity part moves quickly forward (westward), then gradually stops and even turns back (Waldmeier 1955). The p-spot evolves and grows as a result of quick, convergent motion and coalescence of p-polarity pores emerging from the central part of the group (Thomas & Weiss 1992; Zwaan 1992), a nice example of this process is AR 6853 in Bumba, Klvaňa & Kálmán (1995). There is an opinion that the leader spot ceases to grow as soon its forward motion stops (Zwaan 1992). Sometimes in the first days of emergence the spotroup the different polarity pores are mixed, but the motions usually arrange the spots to form a simple bipolar structure. Single, regular spots can be more or less stable, developing a moat, in which magnetic elements (sometimes in the form of pores) move away from them. As p-polarity spots are normally more regular and compact, a larger fraction of long-lived spots is of p-polarity (approximately in a proportion 5:1).

New magnetic flux (new sunspots) emerges significantly more often inside already existing groups. Liggett & Zirin (1985) found ten times larger probability, Harvey & Zwaan (1993) 25 times. The umbrae of the new activity show the dynamic features (quick forward motion of p-polarity spots) typical of young spots, so they can be distinguished from the old spots. Interestingly, collision of the same polarity umbrae of the same wave of activity generally results in their coalescence, whereas same polarity umbrae from different episodes of activity usually remain separate, even "bounce off" like billiard balls in a collision (Kálmán 1980; Kálmán & Nagy 1988). Flow phenomena in the process of sunspot group evolution are described also by Bumba (1983, 1996). There is also the tendency of appearence of several successive sunspot groups in "active complexes/longitudes" or "sunspot nests" (McIntosh 1985; Zwaan 1987).

All these phenomena can be explained with the scenario of emerging Ω-loops from nearly megagauss toroidal fluxtubes, stored immediately beneath the convective zone (Parker 1996). The fluxtube becomes buoyant and unstable (Parker 1955) and emerges to the surface as an Ω-loop. During this emergence in the convective zone it can fragment to several tubes of smaller diameter, these can be the pores, converging to form a larger spot. The velocity of convection in the convective zone is several times larger than the velocity of rise of the buoyant loops (Cowling 1981), so the convective motions can severely disturb the structure of the emerging loop, leading to emerging complex regions. As the energy of the turbulent motion in the convective zone is large, the fluxtubes can be distorted by these motions, so the idea that the proper motions of sunspots is a geometric phenomemon, namely the motion of the intersection points of an emerging rigid magnetic arch with the photosphere does not seem to be valid, only the topological connections are probably conserved (branches coalesce to a larger spot as the fluxtube emerges). The emerging fluxtube leaves behind a turbulent wake, which makes easier for other fluxtubes to emerge (or a new Ω-loop from the same azimuthal fluxtube, after reconnecting at the base of the older Ω). There is another possibility, proposed by Zwaan & Harvey (1994), the successive emergence of flux loops from a stable subsurface magnetic arch.

The quicker forward motion of the p-spots can be attributed to the quicker rotation of the layers immediately below the photosphere (Kosovichev 1996b). As the base of the Ω-loop reconnects, the resulting O-loop loses the connection with the lower layer, and the turbulent convection gradually dissolves it, leading to chaotic, slower motion of older umbrae (Kálmán 1980). In these old, regular spots the magnetic field structure can evolve further than an O-loop (which supposes a bipolar arrangement), even to an "ω-loop", a relatively shallow structure with the magnetic flux of the spot closing to the surroundings, stabilized by the downdraft in its moat cell, but essentially floating, like a cork on the top of the convective zone.

In the active regions described above, we can see the interaction of old, stable, unipolar multiple umbrae ("ω-loops", AR 6555, 6891) or compact bipolar structures ("O-loops", AR 6659, 7070) with emerging new flux. In the case of ARs 6555 and 6891 the new activity emerges on the eastern side of the old, practically unipolar region, and the new spots "flow" around the stable, round obstacle. As the motion in the photosphere and in the subphotospheric layers is highly turbulent, the wake behind the old spot resembles hydrodynamic flow around a cylinder with Reynolds number Re$\sim 10^6$, although some vortices on the interaction boundary can be seen, see e.g. umbra N2 on Fig. 1a of Fontenla et al. (1995). Interesting to note that N2 is of the same magnetic polarity as the "obstacle" N1, so here the interaction looks to be purely hydrodynamical, whereas with P1 of opposite polarity interaction is of magnetohydrodynamical nature: the two X-class flares of March 25 and 26. Also the magnetic interaction dominates in the wake, where in both mentioned ARs opposite polarity umbrae collide, resulting in X-class flares.

For the another two regions, ARs 6659 and 7070, the new flux emerges directly from under the center of the old compact dipole. In AR 6659 new p-polarity appears in between the older p- and f-polarity spots, and from the proper motions it seems, that the new Ω-loop has a $180°$ twist – p-polarity spots stream backwards and f-polarity ones forward. As both the old and the newly emerging flux is significant (Bumba et al. 1983), so the resulting flares are also large. For AR 7070 the new flux emerged also twisted by $90°$, in N-S direction, with a small shift to S, but under the center of the tight old dipole. The new flux was weaker, and a part of the emerging smaller fluxtube became entangled in the old group. This resulted in a single large flare, spreading from the place of the interaction, after the flare the new flux disappeared and the old one also began to shrink.

The prevailing direction of the motions, the "motion axis" in these groups follows Joy's law, the larger is the latitude, the more is the motion axis tilted to the parallels. Very crudely the tilt angle for these sunspot groups is approximately equal to the latitude. This relationship gives larger than average values, this can be connected with the complexity of the groups, caused by longer emergence time, more disturbances in the convective zone, and the consequent stronger effect of Coriolis forces.

5. Conclusions

Newly emerging magnetic flux in older sunspot groups can be distinguished by its proper motions: young sunspots (umbrae) move quicker and generally westward (forward), only in normally oriented dipoles f-polarity umbrae move slowly backwards. In the photosphere umbrae of the new activity behave themselves as separate entities, similar polarities do not coalesce with older umbrae of the same polarity, but both elastic and inelastic collisions between them can be observed, the interaction is mainly hydrodynamic. In collisions of umbrae of different polarity the MHD interaction prevails, leading to flares. Spots of the emerging new activity can flow around old unipolar spots (presumably shallower structures, "ω-loops") westward, like a hydrodynamic flow around a cylinder, forming a wake behind it. Collision of different polarities in the wake can lead to large flares. The presence of old spots can disturb the emergence of the new activity's E-W oriented azimuthal fluxtube, so motions of the new spots are distorted by the flow, the new emerging "Ω-loop" can be stuck between the umbrae of the old, tight dipole, the orientation of the new dipole can be distorted by as much as $180°$. The general direction of the flow around the old spots seems to depend on the latitude, the angle between the motion axis and the E-W direction grows with the latitude. This effect can be attributed to the action of the Coriolis force on the radially emerging "Ω-loop".

The intensive flare activity seems to be connected strongly with the newly emerging magnetic flux, interacting of differently oriented dipoles and the difference of the orientation of the emerging new dipole from the ordinary Hale-Nicholson orientation is also significant. Simply large gradients of magnetic fields (δ-configuration) are not enough, dynamical processes (emergence of new flux, shearing or colliding motions of umbrae of different magnetic polarity) must also be present for large flares.

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References

Ambastha, A., Hagyard, M. J. & West, E.A. 1993, Solar Phys., 148, 277
Brekke, P., Rottman, G. J., Fontenla, J. & Judge, P. G. 1996, ApJ, 468, 418
Brunner, W. 1930, Astron. Mitt. Zürich Nr.124
Bumba, V. 1980, Bull. Astron. Inst. Czechosl., 31, 351
Bumba, V. & Howard, R. 1965, ApJ, 141, 1502
Bumba, V., Klvaňa, M., Kálmán, B. & Győri, L. 1993, A&A, 276, 193
Bumba, V., Klvaňa, M. & Kálmán, B. 1995, A&AS., 109, 355
Bumba, V., Klvaňa, M., Kálmán, B. & Garcia, A. 1996, A&AS., 117, 29
Fontenla, J., Ambastha, A., Kálmán, B. & Csepura, Gy. 1995, ApJ, 440, 894
Gaizauskas, V. 1993, Adv. Space Res., 13, (9)5
Gaizauskas, V., Harvey, K. L., Harvey, J. W. & Zwaan, C. 1983, ApJ, 265, 1056
Harvey, K. & Zwaan, C. 1993, Solar Phys., 148, 85
Jahn, K. 1992, in:J. H. Thomas & N. O. Weiss (eds.), Sunspots: Theory and Observations, Reidel, Dordrecht, 139
Joy, A. H. 1919, ApJ, 49, 167
Kálmán, B. 1980, Thesis, Pulkovo Obs.
Kálmán, B. & Nagy, I. 1988, in: V. E. Stepanov, V. N. Obridko & G. Ya. Smol'kov (eds). Solar Maximum Analysis, Nauka, Novosibirsk, 38
Kane, R. S., Hurley, K. McTiernan, J. M., Sommer, M., Boer, M. & Niel, M. 1996, ApJ, 446, L47
Kosovichev A. G. 1996a, ApJ, 461, L55

Kosovichev A. G. 1996b, ApJ, 469, L61
Liggett, M. A. & Zirin, H. 1985, Solar Phys., 97, 51
Liu, Y., Wang, J., Yan, J. & Ai, G. 1996, Solar Phys., 169, 79
Lindsey, C., Braun, D. C., Jefferies S. M., Woodard, M. F., Fan, Y., Gu, Y., & Redfield, S., 1996a, ApJ, 461, L55
McIntosh, P. 1985, in:L. E. Cram & J. H. Thomas (eds.), The Physics of Sunspots, Sacramento Peak Obs., Sunspot, N.M., 7
Moreno-Insertis, F. & Emonet, T. 1996, ApJ, 472, L53
Newton, H. W. & Nunn, M. L. 1951, MNRAS, 111, 413
Parker, E. N. 1955, ApJ. 121, 491
Parker, E. N. 1996, in: T. Roca Cortés & F. Sánchez (eds.), The Structure of the Sun, Cambridge University Press, Cambridge, 301
Thomas, J. H. & Weiss, N. O. 1992, in: J. H. Thomas & N. O. Weiss (eds.), Sunspots: Theory and Observations, Reidel, Dordrecht, 3
Sakurai, T., Ichimoto, K., Hiei, E., Irie, M., Kumagai, K., Miyashita, M., Nishino, Y., Yamaguchi, K., Fang, C., Kambry, M. & Zhao, Z. 1992, Publ. Astr. Soc. Japan, 44, L7
Schmieder, B., Hagyard, M., Ai, G., Zhang, H., Kálmán, B., Győri, L., Rompolt, B. & Machado, M. E. 1994, Solar Phys., 150, 199
Waldmeier, M. 1952, Ergebnisse und Probleme der Sonnenforschung, Geest & Portig, Leipzig 170
Wang, H. 1992, in: K. L. Harvey (ed.), The Solar Cycle, PASPC, 27, 97
Wang, H. & Wang, J. 1996, A&A, 313, 285
Zhang, H. 1996, ApJ, 471, 1049
Zhu, C. & Shen, L. 1992, Acta Astrophys. Sin., 12, 374
Zirin, H. & Wang, H. 1993, Nature, 363, 426
Zirin, H. & Liggett, M. A. 1987, Solar Phys., 113, 267
Zwaan, C. 1992, in: J. H. Thomas & N. O. Weiss (eds.), Sunspots: Theory and Observations, Reidel, Dordrecht 75

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