On the outer boundary of the sunspot penumbra

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Abstract. Comparison of photographic observations and vector-magnetograph measurements demonstrate, that the outer boundary of the sunspot penumbra — even in complex sunspot groups — closely follows the 0.075 T isogauss line of the total value of the magnetic field, corresponding approximately to the equipartition value in the photosphere. Radio observations also show this feature. The thick penumbra model with interchange convection (Jahn and Schmidt, 1994) gives the best explanation of the penumbral structure.

1. Introduction

The penumbra is the least understood structure of sunspots. Although known from the time of Galileo (Galileo, 1615; Scheiner, 1630), its radial filamentary structure was first recognized with the large telescopes of the 19th century (Secchi, 1870). The first good-quality photographs of the sub-arcsecond penumbral fibrils were made with Stratoscope I in 1957 (Danielson, 1961). Today speckle-restored observations allow to study penumbral details with ground-based telescopes too (Denker, Yang, and Wang, 2001, Sütterlin, 2001).

Real understanding of the physical processes in sunspots began in 1908, when Hale observed strong magnetic fields in them (Hale, 1908). After almost a century, the physics of the sunspot umbra is more or less clear, but the processes occurring in the penumbra even in a regular round sunspot are not fully understood yet (Thomas and Weiss, 1991). In the umbra the strong, almost vertical magnetic field suppresses the convection, thereby reducing the energy reaching the photosphere, so the temperature and brightness is reduced in these places. Unanswered questions are in the remaining umbral structure and in the continuation below the surface. Recently helioseismology gives the possibility to investigate the subsurface structure and dynamics of sunspots (e.g. Kosovichev, Duvall, and Scherrer, 2000; Zhao, Kosovichev, and Duvall, 2001), but the spatial and temporal resolution of these measurements is fairly low yet.

The penumbra is entirely different, in it the magnetic field may be even horizontal (the polarity dividing line between umbrae of different polarities in sunspot groups often lies in the penumbra), but in most places the field is inclined considerably to the surface. As the
photospheric plasma must obey the frozen-in condition of magneto-
hydrodynamics, the penumbral filaments must be aligned along the
magnetic field, but at the same time the surface of the penumbra has
only an insignificant tilt to the horizontal. So the penumbral structural
elements lie in vertical planes, defined by the horizontal component of
the magnetic field (Kalman, 1991). The absolute value of the magnetic
field does not change significantly between bright and dark fibrils, but
the inclination to the surface is definitely smaller in the dark elements
(Title et al., 1993; Wiehr, 2000). Earlier, low-resolution observations
found horizontal field at the penumbra-photosphere boundary (Beckers
and Schröter, 1969), but the latest measurements show, that both the
inclination and the magnetic field value is different from zero at this
boundary (Skumanich, 1991; Solanki, Rüedi, and Livingston, 1992;
Solanki and Schmidt, 1993 and references therein; Martínez Pillet,
1996; Wiehr, 1999).

Recently the fine structure of the penumbral magnetic and veloc-
ity fields was investigated in several papers, using new observational
and reduction methods (Stanchfield, Thomas and Lites, 1997; Ruedi et
al., 1998, 1999; Martínez Pillet, 2000; Westendorp Plaza et al., 2001a,
2001b). These are aimed at understanding the structure and physical
processes in the penumbra, but the more general question, namely
what physical quantity determines the structural boundary between
the photosphere and the penumbra, is also of considerable interest.

The data mentioned above were obtained mostly for regular, round
sunspots, because their structure was supposed symmetrical and so can
be described more easily. However investigation of the interdependence
of penumbral structure and magnetic field is interesting also in complex
sunspot groups for clarifying the processes shaping the penumbra. This
paper describes the behavior of the magnetic field vector on the penum-
bra – photosphere boundary. In Section 2 the observations and results
are presented, in Section 3 these results are discussed in connection
with other data from the literature, finally in Section 4 the conclusions
are drawn.

2. Observations

For the study of the magnetic field at the penumbra – photosphere
boundary four vector magnetograms of the sunspot group NOAA 6555
were selected, together with photographic observations of this group.
Magnetograms were obtained by the NASA Marshall Space Flight
Center (MSFC) vector-magnetograph (Hagyard et al., 1982). Photo-
heliograms were taken from the Debrecen Heliophysical Observatory
archives, they were acquired at its Gyula Observing Station (Dezső, 1982), and were selected according to their quality and near-simultaneity with the magnetograms. Figure 1 displays the photoheliograms for 4 consecutive days in March, 1991, together with the longitudinal (line-of-sight) magnetic field component and with maps of the absolute value of the magnetic field. The longitudinal magnetograms demonstrate, that NOAA 6555 was a magnetically complex spotgroup, with interesting sunspot proper motions and flare activity (Fontenla et al., 1995), consisting of an old, multiple-umbra following polarity spot. Newly emerging umbræ moved around this spot from both sides, causing some large flares in this interaction (Kalman, 1997). A color variant of Figure 1, allowing a better comparison of the photospheric image and the magnetic field strength, and a movie of the proper motions and spot evolution in this active region is included in the CD-ROM supplement, or can be downloaded from the URL http://fenyi.sci.klte.hu/~kalman/penumbra/.

On Figure 1 we can see the complex magnetic structure of the active region, longitudinal magnetic field maps show different polarities in the same penumbra. On the other hand, on the magnetic field absolute value maps the outer boundary of the penumbra closely follows the 0.075 T (750 gauss) isoline. This correspondence is well visible in the process of evolution of the sunspot group, as the penumbra and the total field maps evolve similarly (see the places marked by arrows on Figure 1). As the resolution of the magnetograms is lower, than that of the photographs, the 0.05 – 0.1 T band of the absolute value of the magnetic field is indicated on Figure 1. Large gradients of often opposite polarity fields paired with the low resolution of the magnetogram can shift the isogauss line a little, but there is a good overall correspondence between the outer boundary of the penumbra and the isogausses of the absolute value of the magnetic field. Especially good example is the p- (white) polarity umbra, emerging right at the southeast border of the multiple f-polarity umbra on March 23, and gradually detaching from the common penumbra to March 26. The isogausses in the right column of Figure 1 follow this evolution.

3. Discussion

Earlier observations already reported field strength values of about 0.075 – 0.080 T at the outer boundary of round sunspots (e.g. Solanki, Rüedi, and Livingston, 1992; Martínez Pillet, 1996). Such an almost constant value of field strength at the outer boundary of the penumbra can be observed also for complex sunspot groups, as shown on Figure 1. The observed constancy of the absolute value of the magnetic field on
Figure 1. Longitudinal (line of sight) magnetograms (left column), photographs of AR 6555 (middle column), and isogausses of the total magnetic field (right column) for 1991 March 23–26. Here and on all subsequent images heliographic north is up, east to the left. On longitudinal magnetograms white is positive (preceding) polarity, for the total magnetic field isogausses are drawn at 500, 750, and 1000 gauss. The times of observations for magnetograms (photographs) from top to bottom are: March 23, 18:03 (15:05); March 24, 16:27 (12:33); March 25, 13:38 (14:33); March 26, 13:37 (15:54), times everywhere in UT. (Photographs from Debrecen Heliophysical Observatory, magnetograms from NASA Marshall Space Flight Center.) The slanted lines on the middle two photographs are the images of the (celestial) north-south spider line in the photoheliograph. The outer border of the penumbra follows the isogauss lines of the total magnetic field, and the evolution of both proceeds similarly. This is especially well visible at places marked by arrows in the right column. A color variant of this figure is included in the CD-ROM supplement.
the penumbral outer boundary was already mentioned earlier (Kalman, 1979), but without interpretation.

The same is true for the recent, high-resolution measurements. On Figure 3. of Stanchfield, Thomas and Lites (1997) the penumbral values of the magnetic field strength $|B|$ are all above $\sim$0.08 T. Westendorp Plaza et al. (2001a) find 0.05–0.1 T on the penumbra-photosphere boundary, increasing with height. This supports the results of radio observations (see below), but their analysis can be influenced by the fine structure of the magnetic and velocity fields (Martínez Pillet, 2000).

The value of 0.075 T is approximately equal to the equipartition field value in the photosphere (Galloway and Weiss, 1981; Wiehr, 1996), corresponding to the energy of turbulent convective motions. The exact value of the equipartition field depends on the depth and the model of the convective zone, also the calibration of vector-magnetographs is a difficult problem and model-dependent. Whether the magnetic field falls abruptly to zero at the boundary or continues to the nearby photosphere, can not be decided at this resolution of magnetic measurements, but the change is steep, and magnetic energy, being proportional to the square of the field strength, changes even quicker (Wiehr, 1996, 1999).

Another proof of the controlling influence of the total magnetic field value can be found from radio observations. Gyroresonance emission depends on the absolute value of the magnetic field in the solar corona above sunspots. In a series of VLA observations at 1991 May 7 of NOAA 6615 active region (White, 1999), shown on Figure 2, the 5 GHz and 8.4 GHz contours, corresponding to 0.045 T and 0.075 T, respectively, follow nicely the outline of the penumbra of this complex and compact sunspot group, whereas the 15 GHz emission (0.135 T) is observed mainly above umbrae (and in the middle of the group above the neutral line in a $\delta$-configuration, which leads to stronger coronal activity).

Substantial amount of magnetic flux, and even more heat flux leaves the sunspot through the penumbra, so it needs lateral energy flow from the surroundings. This is possible through interchange convection (Schmidt, 1991; Jahn, 1991; Jahn and Schmidt, 1994), in which magnetic fluxtubes, or sheets are heated at the outer boundary of the spot (the magnetopause), then moving upwards and inwards in a vertical plane they supply energy to the penumbra, whereas cooler material flows downwards and outwards. Observations support this model: Penumbral filaments lie in vertical planes, defined by the horizontal component of the magnetic field (Kalman, 1991), inclination (but not strength) of the field varies in bright and dark filaments (Title et al., 1993; Wiehr, 2000). SOHO MDI measurements (Norton et al., 1999) show enhanced power of intensity oscillations in the range 0.5–1.0
Figure 2. Optical and radio observations of AR 6615 for 1991 May 7. (a) photograph of the spotgroup at 06:16 UT (Debrecen Observatory), serving also as background for isolines. (b) isogausse of the total magnetic field at 17:58 UT (NASA MSFC), the lowest one is 450 gauss, every consecutive one is 300 gauss higher. (c) Kitt Peak longitudinal magnetogram at 14:34 UT, white is positive (preceding) polarity. (d)-(f) are VLA observations of gyroresonance emission of the solar corona, taken from White et al, (1999). The contours begin at 10% of the maximum brightness and are 10% apart. (d) shows emission at 5 GHz, corresponding to a total coronal magnetic field of 450 gauss, (e) and (f) display emission at 8.4 GHz and 15 GHz, corresponding to 750 and 1350 gauss, respectively.

mHz (16.7–33.3 min period) in a ring with filamentary structure right at the penumbra-photosphere boundary, and magnetic field strength oscillations also in this period range show filamentary structure in the penumbra, just as it should be for the interchange convection (Figure 3).

The thick penumbra model (Jahn and Schmidt, 1994, Jahn, 1996) supposes, that from some depth to the surface the the magnetopause (penumbra - photosphere boundary) transmits some energy from the surrounding convective zone, and this energy is distributed in the penumbra by the interchange convection. This model uses the monolithic sunspot convention, i.e. the magnetic field of the sunspot is represented by a single fluxtube of varying cross-section from the surface to the depth of 15-20 Mm. The depth of the penumbra is supposed to be about 4-5 Mm. Recent results (Zhao, Kosovichev, and Duvall, 2001) seem to contradict the monolithic sunspot model, showing strong transverse flows at depth ≈5Mm.
It is instructive to follow the change of the equipartition magnetic field value with depth, and compare with the magnetic field at the magnetopause. Figure 4 shows such a comparison, where the equipartition field values were computed from the energy density of the convective motions (R. Stein, private communication) in a 9 Mm deep simulation of the convective zone (Stein and Nordlund, 1994), the magnetic field value at the magnetopause is extrapolated down from the surface value, scaled according to the the cross-section of the model of Jahn and Schmidt. The two curves intersect at the depth of about 6 Mm, which indicates a change of the type of interaction at this depth. This gives a natural explanation of the depth of the thick penumbra model: above 6 Mm the energy, carried by convective motions, can partly penetrate through the magnetopause. The controversy between the monolithic and the cluster model (Zhao, Kosovichev, and Duvall, 2001) can be resolved, if a change of type with the evolution of the sunspot is supposed (Kalman, in preparation): younger sunspots at emergence have deep connections, which is severed later by the turbulent convection below 6 Mm. Stable and decaying sunspots are shallow, and are hold together by their moat cell (Hurlburt and Rucklidge, 2000; Zhao, Kosovichev, and Duvall, 2001) until the convection finally erodes their magnetic field concentration.
4. Conclusion

Observations show that the outer boundary of the sunspot penumbra even in complex active regions follows the isogaus line of the total magnetic field corresponding approximately to the equipartition field value at the surface (Figure 1). The observations also support the thick penumbra model with interchange convection (Jahn and Schmidt, 1994), the change of the ratio of the equipartition field value and the field value at the magnetopause boundary with depth gives a natural depth of the penumbra about 5–6 Mm. The magnetic field in the penumbra is not strong enough to stop the convection, but severely alters its nature, leading to formation of interchange convection. The enigmatic penumbra at last seems to be understandable.

Acknowledgements

The author thanks Dr. Mona Hagyard of NASA MSFC for sending the magnetograms used, Drs. R.F. Stein and H. Spruit for sending their respective convective zone model data, and Drs. H.U. Schmidt and K. Jahn for informations about their thick penumbra model, also the anonymous referee for suggesting more literature supporting the conclusion. Kitt Peak Observatory magnetogram was taken from NSO/Kitt...
Peak Internet archives. NSO/Kitt Peak data used here are produced co-operatively by NSF/NOAO, NASA/GSFC and NOAA/SEL. Debrecen Observatory photographic observations were made by I. Lengyel. This research has made use of NASA’s Astrophysics Data System Abstract Service. Part of this work was supported by grant T-025737 of the Hungarian Scientific Research Fund (OTKA).

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