ON THE OUTER BOUNDARY OF THE SUNSPOT PENUMBRA

BÉLA KÁLMÁN
Heliophysical Observatory of the Hungarian Academy of Sciences
P.O.Box 30., H-4010 Debrecen, Hungary. (e-mail: kalman@tigris.klte.hu)

(Received 10 December 2001; accepted 29 January 2002)

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 iso-gauss 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-arc-sec penumbral fibrils were made with Stratoscope I in 1957 (Danielson, 1961). Today, speckle-restored observations allow us 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 are more or less clear, but the processes occurring in the penumbra even in a regular round sunspot are not yet fully understood (Thomas and Weiss, 1991). In the umbra the strong, almost vertical magnetic field suppresses the convection, thereby reducing the energy reaching the photosphere, so that the temperature and brightness are reduced in these places. Unanswered questions concern the remaining umbral structure and the continuation below the surface. Recently, helioseismology provides a possibility to investigate the sub-surface structure and dynamics of sunspots (e.g., Kosovichev, Duvall, and Scherrer, 2000; Zhao, Kosovichev, and Duvall, 2001), but the spatial and temporal resolutions of these measurements are still fairly low.

The penumbra is entirely different: in it the magnetic field may even be horizontal (the polarity dividing line between umbrae of different polarities in sunspot groups often lies within 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 magnetohydrodynamics, the penumbral filaments must be aligned

Solar Physics **209:** 109–117, 2002.

along the magnetic field, but at the same time the surface of the penumbra has only an insignificant tilt to the horizontal. Thus, the penumbral structural elements lie in vertical planes, defined by the horizontal component of the magnetic field (Kálmán, 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 a 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 are 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 velocity fields was investigated in several papers, using new observational and reduction methods (Stanchfield, Thomas, and Lites, 1997; Rüedi *et al.*, 1998; Rüedi, Solanki, and Keller, 1999; Martínez Pillet, 2000; Westendorp Plaza *et al.*, 2001a, b). These are aimed at understanding the structure and physical processes in the penumbra, but the more general question, namely which 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 is supposed to be symmetrical and so can be described more easily. However, investigation of the interdependence of penumbral structure and magnetic field is also interesting in complex sunspot groups for clarifying the processes shaping the penumbra. This paper describes the behavior of the magnetic field vector on the penumbra – 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, and 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). Photoheliograms were taken from the Debrecen Heliophysical Observatory archives, acquired at its Gyula Observing Station (Dezsö, 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 maps of the absolute value of the magnetic field. The longitudinal magnetograms demonstrate that NOAA 6555 was a magnetically complex spot group, with interesting sunspot proper motions and flare activity (Fontenla *et al.*, 1995), consisting of

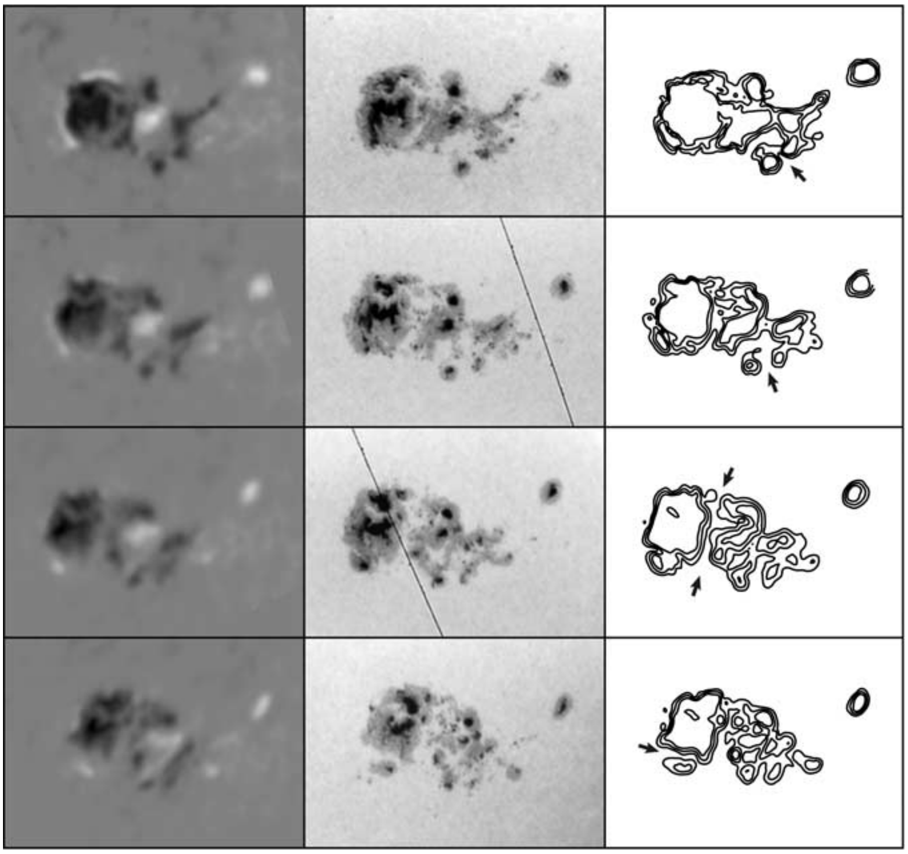

Figure 1. Longitudinal (line-of-sight) magnetograms (*left column*), photographs of AR 6555 (*middle column*), and iso-gauss lines of the total magnetic field (*right column*) for 23–26 March 1991. Here and on all subsequent images heliographic north is up, east to the left. On longitudinal magnetograms *white* is positive (preceding) polarity, for the total magnetic field isogauss lines are drawn at 500, 750, and 1000 G. The times of observations for magnetograms (photographs) *from top to bottom* are: 23 March, 18:03 (15:05); 24 March, 16:27 (12:33); 25 March, 13:38 (14:33); 26 March, 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.

an old, multiple-umbra following polarity spot. Newly emerging umbrae moved around this spot from both sides, causing some large flares in this interaction (Kálmán, 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 are included in the CD-ROM supplement, or can be downloaded from *http://fenyi.sci.klte.hu/~kalman/penumbra/.*

In 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, in maps of the absolute magnetic field value the outer boundary of the penumbra closely follows the 0.075 T (750 G) iso-line. This correspondence is apparent 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 in Figure 1. Large gradients of opposite polarity fields paired with the low resolution of the magnetogram can often shift the isogaus line, a little, but there is a good overall correspondence between the outer boundary of the penumbra and the iso-gausses of the absolute value of the magnetic field. An especially good example is the case of p-polarity umbra (white), emerging right at the southeast border of the multiple f-polarity umbra on 23 March, which was gradually detaching from the common penumbra to 26 March. The iso-gausses 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 also be observed for complex sunspot groups, as shown in Figure 1. The observed constancy of the absolute value of the magnetic field on the penumbral outer boundary has been mentioned earlier (Kálmán, 1979), but without interpretation.

The same is true for recent, high-resolution measurements. In Figure 3 of Stanchfield, Thomas, and Lites (1997), the penumbral values of the magnetic field strength $|\mathbf{B}|$ are all above ~ 0.08 T. Westendorp Plaza *et al.* (2001a) find 0.05–0.1 T at 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 cannot 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).

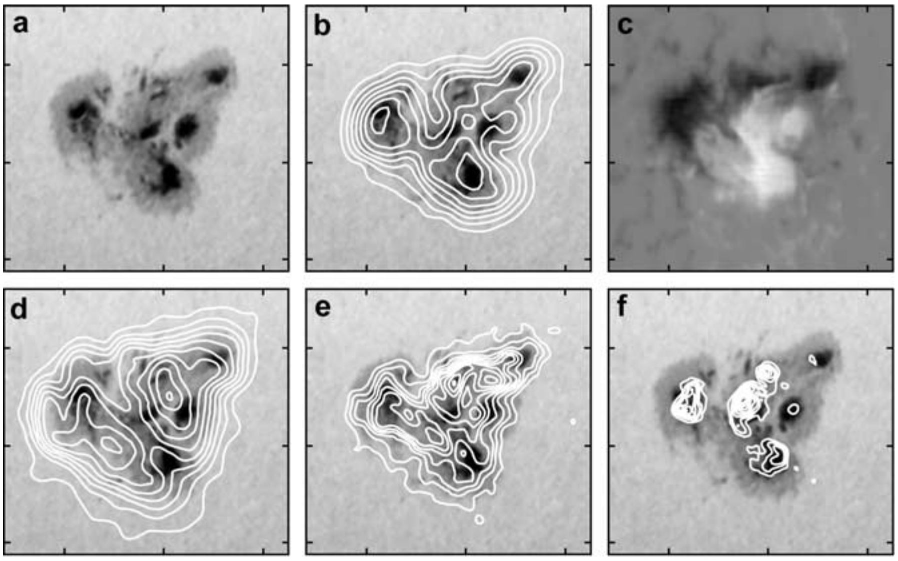

Figure 2. Optical and radio observations of AR 6615 for 7 May 1991. (a) Photograph of the spot group at 06:16 UT (Debrecen Observatory), serving also as background for iso-lines. (b) Isogauss lines of the total magnetic field at 17:58 UT (NASA MSFC), the lowest one is 450 G, every consecutive one is 300 G higher. (c) Kitt Peak longitudinal magnetogram at 14:34 UT, *white* is positive (preceding) polarity. (d)–(f) VLA observations of gyro-resonance emission of the solar corona, taken from White (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 G, (e) and (f) display emission at 8.4 GHz and 15 GHz, corresponding to 750 and 1350 G, respectively.

Another proof of the controlling influence of the total magnetic field value can be found in radio observations. Gyro-resonance emission depends on the absolute value of the magnetic field in the solar corona above sunspots. In a series of VLA observations at 7 May 1991 of NOAA active region 6615 (White, 1999), shown in Figure 2, the 5 GHz and 8.4 GHz contours, corresponding to 0.045 T and 0.075 T, respectively, nicely follow 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 δ-configuration, which leads to stronger coronal activity).

Substantial amounts of magnetic flux and even more heat flux leave 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 flux tubes or sheets are heated at the outer boundary of the spot (the magnetopause), then, moving upwards and inwards in a vertical plane, 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 (Kálmán, 1991). Inclination (but not strength) of the field varies in bright and dark fila-

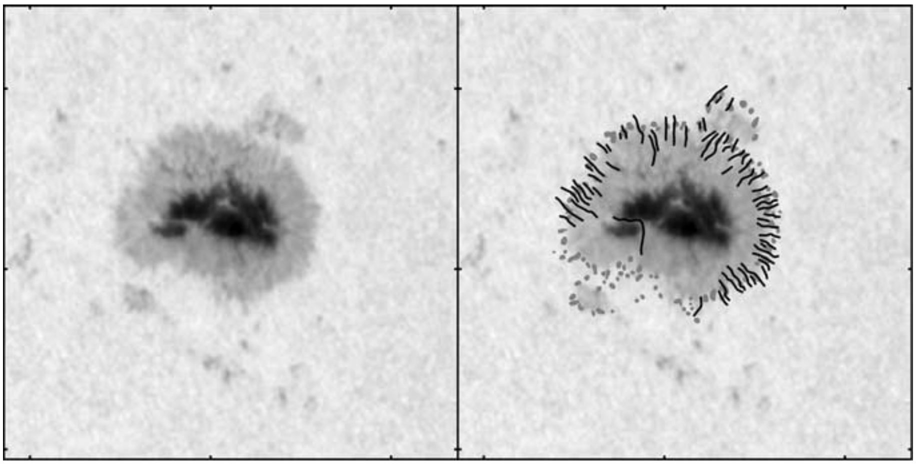

Figure 3. MDI observations of the leader spot of AR 8113 for 2 December 1997, taken from Norton *et al.* (1999). The *left image* is the average photospheric intensity, on the *right image* the places are marked where the intensity fluctuations (*grey dots*) or the longitudinal magnetic field fluctuations (*black lines*) in the 0.5 – 1.0 mHz range (16.7 – 33.3-min period range) are maximal.

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

The thick penumbra model (Jahn and Schmidt, 1994; Jahn, 1996) supposes that from some depth to the surface the magnetopause (penumbra – photosphere boundary) transmits some energy from the surrounding convective zone, and that 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 flux tube 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, however, to contradict the monolithic sunspot model, showing strong transverse flows at depth of ≈ 5 Mm.

It is instructive to follow the change of the equipartition magnetic field value with depth, and compare this 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.F. 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 a 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

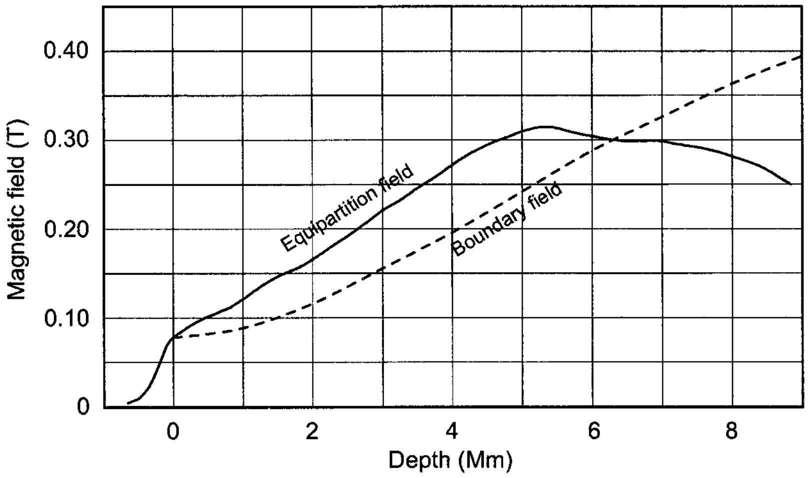

Figure 4. The variation with depth of the equipartition magnetic field (Stein, private communication) in a 9 Mm deep simulation of the convective zone (Stein and Nordlund, 1994) and of the field strength on the outer boundary of the sunspot (the magnetopause) according to the model of Jahn and Schmidt (1994).

thick penumbra model, namely that 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 (Kálmán, in preparation). Here younger sunspots at emergence have deep connections, which are affected by turbulent convection below 6 Mm. Stable and decaying sunspots are shallow, and are held 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 isogauss 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), where the change of the ratio of the equipartition field value and the field value at the magnetopause boundary gives a natural depth of the penumbra of 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 thus 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 information about their thick penumbra model. We are also grateful to an 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 cooperatively 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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