New insights on penumbra magneto-convection

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Abstract. Fully-fledged penumbra is by now a well characterised phenomenon from an observational point of view. Also, very sophisticated MHD simulations are providing us with good insights on the physical mechanisms possibly running behind the observed processes. Yet, how this penumbral magneto-convection sets in is still an open question. Due to the fact that penumbra formation is a relatively fast process (of the order of hours), it has eluded its observation with sufficient spatial resolution by both, space- and ground-based solar observatories. Only recently, some authors have witnessed the onset of both *orphan* and *sunspot* penumbrae in detail. We are one of those. In July 2009, we observed the early stages of the NOAA 11024 leading sunspot while developing its penumbra. The spectro-polarimetric data lead us to new observational findings. In this contribution, we put into context our and other authors' results to draw the overall picture of sunspot formation. Most important, the comparison on the properties of orphan and sunspot penumbrae lead us to the conclusion that the formation of penumbrae is *not just one mechanism*. Rather, observations show that flux emergence is behind the formation of orphan penumbra while flux fallen from chromospheric layers leads to the formation of penumbra in sunspots. A major conclusion follows: the sole responsible for penumbral magneto-convection to set in are *stably inclined fields*. The mechanisms generating these inclined fields may differ. This conclusion, together with the recent finding by Jurčák et al. on a canonical value of the vertical component of the magnetic field blocking the action of penumbral magneto-convection in umbral areas, are a crucial step forward to our understanding on the coupling of solar plasmas and magnetic fields in penumbral atmospheres.

1. Motivation

Although stable penumbra seems to be a well characterised phenomenon from both the observational and modelling point of view, the mechanisms behind its onset and establishment in the photosphere has not been studied in detail. Recent observations of active regions taken with high spatial resolution by various independent research teams have lead to new discoveries on the process of penumbra formation: Schlichenmaier et al. (2010a,b, 2011, 2012) report on 4.5 h during which a protospot develops penumbra while accumulating magnetic flux from the active region flux emergence site. They observe bipolar loops emerging to the solar surface continuously carrying new flux to the protospot on the one side while penumbra forms in the opposite side. They also reported for the first time in an unexpected counter-Evershed flow in the protospot boundary preceding penumbra formation. Rezaei et al. (2012) found signatures of a canopy at photospheric level around the protospot before the penumbra appearance at the solar surface. Jurčák (2011) discovered a natural constant in the umbra-penumbra boundary of stable sunspots: a canonical value of 1.86 kG of the vertical component of the magnetic field. Jurčák et al. (2015) and Jurcak et al. (2016) confirmed this canonical value as a natural border for penumbral magneto-convection during penumbra formation and development. Shimizu et al. (2012) and Romano et al. (2013) found indications of a penumbral halo at chromospheric level prior to the formation of penumbra in the photosphere. Romano et al. (2013, 2014) and Murabito et al. (2016) put these findings into the context of magnetic flux at chromospheric height bending down to the photosphere leading to penumbra formation at the solar surface. They also found signatures of (counter Evershed) inflowing material similar to those reported by Schlichenmaier et al. (2010a), and they discuss on the siphon nature of those in the context of falling flux tubes. We report in Sect. 2 on the properties of this siphon counter-Evershed flow observed in the vicinity of the protospot persistent for about one hour prior to the onset of the Evershed flow and corresponding penumbra, as seen in the solar surface. Comparison with emerging bipoles carrying new flux to the solar surface strengthen the fact that the siphon flows are not related to flux emergence processes. Interestingly, Bellot Rubio et al. (2008) reported on sunspot penumbrae decaying by the inverse process, i.e., field lines rising from the photospheric level onto the chromosphere.

From the modelling point of view, several studies help to put into context the observational findings: Hurlburt & Rucklidge (2000) and Simon & Weiss (1970) find an increasing inclination (w.r.t. the normal to the solar surface) of the magnetic field with increasing flux in sunspot models. Wentzel (1992) proposed a penumbral model fed by flux tubes fallen onto the photosphere owing to the upwelling of a mass flow in the inner footpoint (within the umbra) of field lines closing up (submerging) in the surroundings of a sunspot.

Another form of penumbra is the so-called *orphan penumbra*. Those are penumbrae not coupled to an umbra. They show similar properties to sunspot penumbrae except for the missing more vertical (sunspot) background component (Jurčák et al. 2014b). Lim et al. (2013) and Zuccarello et al. (2014) found orphan penumbrae originating from emerging magnetic field trapped at photospheric level by the pre-existing overlying fields in areas of complex topology in active regions, typically nearby the polarity inversion lines. Jurčák et al. (2014b) found orphan penumbra that decayed by the inverse process, i.e., by flux submerging beneath the solar surface.

The main aim of this contribution is to put for the first time all these major findings together. They lead to striking conclusions on penumbral magneto-convection, hence, challenging to tackle the still unresolved questions, e.g., the process causing the fall and stable inclination of the field lines in sunspots leading to penumbra formation and the inhibition of the penumbral magneto-convection by vertical fields above the canonical value (1.8 kG) discovered by Jurčák (2011).

2. The counter-Evershed flow – A siphon flow precursor of sunspot penumbra formation

In Schlichenmaier et al. (2010a), we reported on the presence of a counter-Evershed flow during the early stages of a protospot and previous to the appearance of the penumbra in the solar surface. After a more detailed analysis, we know by today that this corresponds to a *siphon flow* developed at a granular scales. Fig. 1 presents one example of the observed siphon flows, marked in the leftmost boxes of the overall maps of intensity (a), line-of-sight velocities (b), magnetic field strength (c) and magnetic field inclination in the local reference frame (d). A close-up of the selected event is shown on the panel labeled with 'siphon flow'.

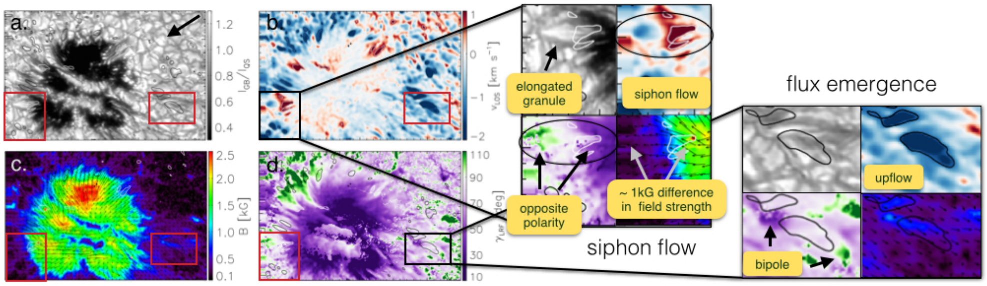


Figure 1. Example of a siphon counter-Evershed flow in an area of penumbra formation. The four left panels display the leading sunspot of NOAA 11024 as seen in intensity (a), line-of-sight velocities (b), magnetic field strength (c) and inclination (d), at a given time during sunspot evolution. The rectangles mark the positions of the areas seen in the two close-ups on the right: an example of a siphon flow (left) and, for comparison, a selected event in the AR flux emergence area (right). The black arrow in panel (a) points towards disc centre.

The physical parameters have been retrieved by applying inversion techniques (SIR code, Ruiz Cobo & del Toro Iniesta 1992). We refer the reader to a forthcoming contribution for a detailed description of the data analysis.

In the corresponding close-up panels, one can see in intensity the elongated granule outlining the blue-white-red patch marked in the velocity map. The event lies close to parallel to the line of symmetry of the spot (see black arrow pointing to disc centre in the (a) panel). This means that the blue-white-red patch can be interpreted as an upflow (blue) starting in the leftmost footpoint of the elongated granule, inflowing towards (blue-to-white) the rightmost footpoint where it finally downflows (red). The topology of the field can be partially inferred from the magnetic inclination map: the leftmost footpoint has negative (green) polarity, it becomes close to horizontal (90 deg, white) along the elongated granule and ends up in an area of positive polarity (violet). The difference in magnetic field strength of about 1.5 kG between the footpoints, generates the observed siphon (in-)flow owing to the strong (magnetic) pressure imbalance. Yet, what is causing the formation of the outermost (leftmost) footpoint of negative polarity? Some mechanism must have dragged the field lines down to the sub-surface layers.

In order to discard the action of flux emergence as the mechanism giving rise to this kind of events, we show an example characteristic of emergent bipolar features from the site of the active region flux emergence area. It can be seen in the rightmost panels of Fig. 1. It corresponds to abnormal/elongated granulation as seen in intensity.

This is a well-known fact found in both observations and simulations of flux emergence: the granules stretch under the action of and along inclined fields. The magnetic structure shows a bipolar pattern with differences in magnetic field strength of 0.4 kG. Yet, the velocity pattern exhibits a distinctive strong upflow (blue) all over the emergent bulk occasionally accompanied by localised downflows (red) footpoints at a given stage during the emergence process, possibly do to the draining down of the plasma excess elevated during the emergence process. Thus, by comparing these kind of events, we can rule out magnetic field emergence as the mechanism behind the siphon flows observed prior to the penumbra formation in sunspots.

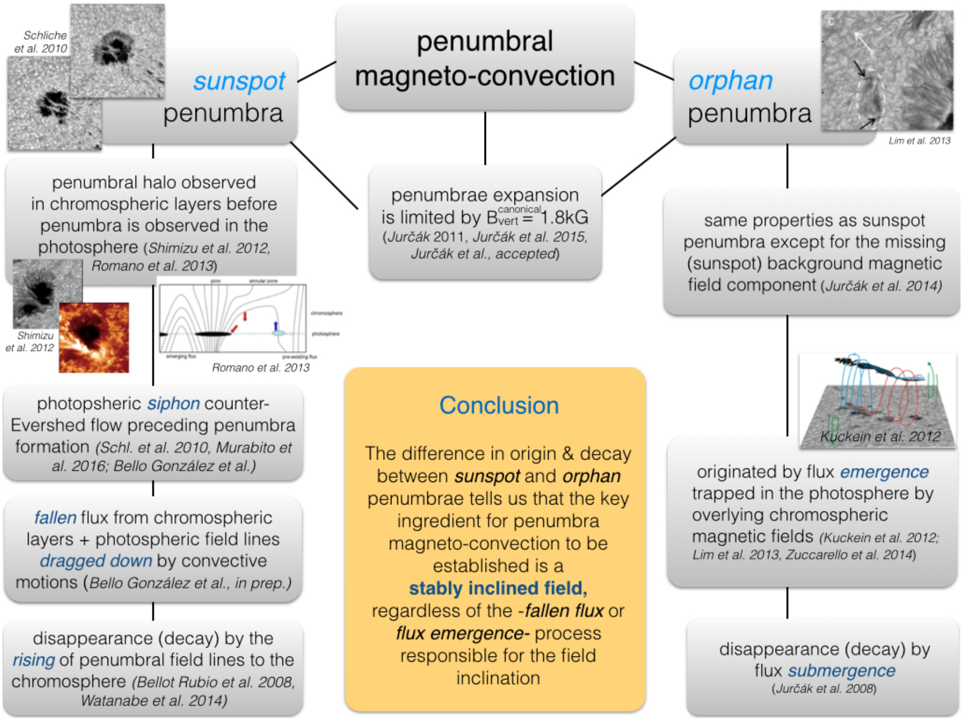
This finding together with those by Rezaei et al. (2012); Shimizu et al. (2012); Romano et al. (2013, 2014) and Murabito et al. (2016) rather hints towards the action of a mechanism bending the field lines from chromospheric layers down to the photosphere and subsequently dragged down to sub-photospheric layers by the action of convective motions. Once the field lines have been submerged, and due to the strong magnetic pressure imbalance between the footpoints outside and inside the protospot, a siphon flow develops. The persistent (of around 1 h) mass load of this flow onto the field lines might further contribute to stably incline the field necessary for the penumbra to eventually set in (see discussion on Sect. 3).

3. New insights on penumbral magneto-convection

Most significant and new conclusions about penumbral magneto-convection arise from comparing *sunspot* and *orphan* penumbrae. The main properties concerning their formation and decay are summarised schematically in Fig. 2.

Sunspot penumbra formation. Observations on sunspot penumbra formation show clear indications of the existence of a penumbra at chromospheric level before it becomes apparent in the photosphere (Shimizu et al. 2012; Romano et al. 2013, 2014). The existence of a magnetic canopy extending beyond the photometric protospot boundary (see Rezaei et al. 2012) is a further indication of the existence of the penumbra before its actual appearance in the solar surface. These findings together with the presence of siphon counter-Evershed flows preceding the penumbra formation, like those discussed in Sect. 2 and by Romano et al. (2014) and Murabito et al. (2016), give evidence of magnetic field lines fallen from chromospheric layers onto the photosphere and subsequently submerged to give birth to sunspot penumbrae in the solar surface. This 'falling' mechanism is possibly a combination of both, (a) an increasing in inclination of the field lines from high layers onto the photosphere as a result of increasing flux (see, e.g., Hurlburt & Rucklidge 2000; Simon & Weiss 1970) observed in the developing sunspot and, (b) the submergence of those field lines below the photospheric level dragged down by the convective motions in the photosphere. Indications of the action of convective motions in the submergence of photospheric field lines are given by changes from negative to positive values of the Poynting flux measured in simulations of quiet-sun areas at heights of up to 150 km above the τ=1 level (Steiner, private communication). Tortosa-Andreu & Moreno-Insertis (2009) also discuss an event on magnetic field lines submerged into subphotospheric layers by the downdraft of a forming intergranular lane (see their Figs. 5 and 6).

Wentzel (1992) proposed the *fallen magnetic flux tubes* model in which magnetic flux tubes fall onto the photosphere owing to the action of an upwelling of mass at



penumbral magneto-convection

sunspot penumbra

penumbral halo observed in chromospheric layers before penumbra is observed in the photosphere (*Shimizu et al. 2012, Romano et al. 2013*)

photopsheric *siphon* counter-Evershed flow preceding penumbra formation (*Schl. et al. 2010, Murabito et al. 2016; Bello González et al.)*

fallen flux from chromospheric layers + photospheric field lines *dragged down* by convective motions (*Bello González et al., in prep.)*

disappearance (decay) by the *rising* of penumbral field lines to the chromosphere *(Bellot Rubio et al. 2008, Watanabe et al. 2014)*

penumbrae expansion is limited by $B_{\rm vert}^{\rm canonical} = 1.8$kG (*Jurčák* 2011, *Jurčák et al. 2015, Jurčák et al., accepted*)

Conclusion

The difference in origin & decay between ***sunspot*** and ***orphan*** penumbrae tells us that the key ingredient for penumbra magneto-convection to be established is a **stably inclined field,** regardless of the -***fallen flux*** or ***flux emergence***- process responsible for the field inclination

orphan penumbra

same properties as sunspot penumbra except for the missing (sunspot) background magnetic field component (*Jurčák et al. 2014)*

originated by flux *emergence* trapped in the photosphere by overlying chromospheric magnetic fields *(Kuckein et al. 2012; Lim et al. 2013, Zuccarello et al. 2014)*

disappearance (decay) by flux *submergence* (*Jurčák et al. 2008*)

Figure 2. Ingredients involved in penumbral magneto-convection.

their inner (umbral) footpoint. For that, the model premises that the field lines should be 'closed' within the sunspot surroundings. The eventual appearance of penumbral filaments in the solar surface with the onset of the Evershed flow within the umbra (Bello González et al., in preparation) and extending outwards would go in line with this model.

Sunspot penumbra decay. Checking in the literature for possible similarities in the mechanism(s) leading to penumbra formation and decay, we find that Bellot Rubio et al. (2008) reported on penumbra disappearance owing to the rise of photospheric magnetic field lines onto the chromosphere during sunspot decay. Watanabe et al. (2014) found similar results for a rudimentary penumbra. These findings strengthen the existence of a similar, yet inverse, mechanism for sunspot penumbra decay, i.e., fall(rise) from(to) the chromosphere acting behind penumbra formation(decay).

Orphan penumbra formation. Penumbrae are also observed in areas with complex magnetic topology, e.g., areas close to the polarity inversion line of active regions. These penumbrae are typically found not to be coupled to any umbra and therefore they are referred as to *orphan* penumbrae.

Jurčák et al. (2014b) compared sunspot and orphan penumbrae and found similar properties (temperature, Evershed flows,...), except for an important ingredient: orphan penumbra shows no signatures of the sunspot, more vertical, background component. I.e., *penumbral magneto-convection does not need of an uncombed structure to exist*.

Furthermore, Kuckein et al. (2012), Lim et al. (2013) and Zuccarello et al. (2014) found clear indications of orphan penumbrae formed by flux emergence in complex active regions areas. This emerging flux is kept trapped at photospheric level by overlying pre-existing magnetic fields and, it therefore cannot rise further up. I.e., orphan penumbra forms out of flux emerged from the convection zone onto the photosphere which cannot rise further up blocked by the overlying magnetic field topology (typically characterised by the presence of filaments).

Orphan penumbra decay. Jurčák et al. (2014b) reported on the decay of the studied orphan penumbra by flux *submergence* beneath the solar surface. Thus, contrary to sunspot penumbra, orphan penumbra forms(decays) out of flux emergence(submergence) from(into) the sub-photospheric layers.

In summary, the comparison between sunspot and orphan penumbrae tells us that the penumbral magneto-convection can be triggered by different mechanisms. Yet, most important, *the crucial ingredient of the penumbral mode of magneto-convection is the presence of stably inclined (horizontal) fields*, regardless of the mechanism inclining the field.

Conclusions. These major findings by various authors lead us to extraordinary conclusions:

1. There is no one sole mechanism behind penumbra formation, i.e., penumbral magneto-convection can be generated by distinct mechanisms.
2. The necessary condition for penumbral magneto-convection to set in is *stably inclined (horizontal) magnetic fields*. Independently of the mechanism causing the inclination of the field.
3. The penumbral mode of magneto-convection does not need of the more vertical (sunspot) background component to take action.
4. Penumbral magneto-convection can be established in areas of umbral magneto-convection as well as in granulation. Yet, values of the vertical component of the magnetic field above $\sim$1.8 kG inhibit the action of this mode of penumbral magneto convection, but not the umbral mode.

4. Scenario for sunspot formation

In this contribution, we also want to summarise and build up a scenario for sunspot formation based on our findings on sunspot and penumbra formation, outlined in the articles by Schlichenmaier et al. (2010a), Schlichenmaier et al. (2010b), Schlichenmaier et al. (2011), Schlichenmaier et al. (2012), Rezaei et al. (2012), Bello González et al. (2012), Jurčák (2011), Jurčák et al. (2014a), Jurčák et al. (2015) and Jurcak et al. (2016) and in context with observational and theoretical results by many other authors:

1. The magnetic field of the AR may originally stem from one thick, deeply rooted flux rope.

2. During its rise through the convection zone, the rope splits into smaller strands.
3. Different twists develop for each strand owing to the effect of turbulent convective buffeting during the flux rise.
4. When emerging at the surface, the various flux strands appear first as small loops of flux tubes in granular-scale units. These emerging loops are outlined by horizontal fields stretching the granules and are connected by footpoints of opposite polarity (Schlichenmaier et al. 2010b).
5. As the loops rise, the magnetic footpoints move apart from each other along the AR axes migrating towards the polarity they belong.
6. The magnetic footpoints of same polarity thus combine to form pores with their own field twists (Bello González et al. 2012).
7. Then, pores coalesce to form a protospot (Zwaan 1985, 1987; Schlichenmaier et al. 2010a). During the coalescence, granules get trapped giving rise to light bridges.
8. At this stage, the protospot already shows signatures of a canopy (Rezaei et al. 2012), i.e., the protospot flux rope funnels out with height.
9. Pores are the components (umbral cores) of the protospot, yet, they keep their magnetic identity, showing their own signatures like, e.g., magnetic twists (Bello González et al. 2012).
10. In the protospot, the less magnetised light bridges are the natural gate of the new incoming flux provided by the AR emergence site. Light bridges eventually (magnetically) saturate (Rezaei et al. 2012).
11. The magnetic flux is re-arranged within the physical boundaries of the magnetic funnel of the forming spot as it continues gathering new flux from the site of emergence (Schlichenmaier et al. 2010a; Rezaei et al. 2012).
12. At this stage, the penumbra can only be seen in chromospheric layers (Shimizu et al. 2012; Romano et al. 2013).
13. The field funnels further out as the magnetic flux increases, i.e., the field at the edge of the spot flux tube gets more and more inclined (horizontal) with increasing flux (Hurlburt & Rucklidge 2000; Simon & Weiss 1970). This effect is most prominent in the side of the spot opposite to the emergence site.
14. As the spot continues gathering flux on the emergence-site side, the protospot field lines reach a critical inclination, close to horizontal, on the opposite side. At this stage, the field lines are possibly dragged down and submerged by the convection.
15. The (horizontal) submerging field lines stretch the granules at the spot boundary. These field lines exhibit footpoints of opposite polarity: one rooted within the protospot, where it originally belongs, and the other pinned in the spot nearby. The footpoints show a difference in magnetic field strength of ~1.5 kG (Sect. 2).

16. Owing to the pressure imbalance between the footpoints of these submerging field lines caused by the strong difference in magnetic field strength, a *siphon flow* develops following the magnetic field lines. This inflow is counter to the Evershed flow (Schlichenmaier et al. 2012) and develops at granular scales (see Sect. 2 and Murabito et al. 2016) and larger (several granules apart) scales (Romano et al. 2013, 2014), where the inclined fields of the spot submerge.
17. At this stage, penumbral-like filaments can be observed in layers where the line-minimum of photospheric lines form (Bello González et al., in preparation).
18. After few hours, the counter-Evershed flow is overtaken by the onset of the Evershed flow and the formation of stable penumbral filaments at continuum level, i.e., penumbral magneto-convection, establishes.
19. Penumbral magneto-convection originally develops from umbral areas and expands over the surrounding granulation. The further expansion of penumbra into umbral areas is hindered by a critical value (1.86 kG) of the *vertical component* of the magnetic field (Jurčák 2011; Jurčák et al. 2014a, 2015; Jurcak et al. 2016).
20. Penumbra develops in different segments around the spot. Firstly, in the spot side away from the emergence site where inclined fields can stably settle. Only various hours to a day later, when the emergence ceases, penumbra fully sets all around the spot. Within the next days, the sunspot light bridges might 'submerge' thus hiding in the darkness of umbral magneto-convection (Schlichenmaier et al. 2016) to later reappear breaking up the sunspot during the decay phase (Garcia de La Rosa 1987).
21. Eventually, the AR thick rope emerges in total, and a mature sunspot with its distinct umbra with a complete penumbra forms.

5. Outlook

Observations have lead us to important conclusions on magneto-convection in penumbrae. Yet, many questions remain still open:

- Is the increase in magnetic flux in the protospot the responsible of the bending of the field lines from chromospheric level to the photosphere to form sunspot penumbra? Note that pores with larger flux than small sunspots are observed.
- Up to which height in the photosphere can the action of the convective motions drag the field lines down to sub-photospheric layers leading to the observed siphon flows preceding the onset of sunspot penumbra in the solar surface?
- Why above a critical value (1.8 kG), the vertical magnetic field inhibits the penumbral mode of magneto-convection and not the umbral mode?

We would like to challenge numerical experiments tackling these questions, pursuing the full characterisation of both the magneto-convection running in penumbrae and the process behind penumbra formation in sunspots.

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