Solar and Stellar Magnetic Fields: Origins and Manifestations
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Revisiting the building blocks of solar magnetic fields by GREGOR

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Abstract. The Sun is our dynamic host star due to its magnetic fields causing plentiful of activity in its atmosphere. From high energetic flares and coronal mass ejections (CMEs) to lower energetic phenomena such as jets and fibrils. Thus, it is of crucial importance to learn about formation and evolution of solar magnetic fields. These fields cover a wide range of spatial and temporal scales, starting on the larger end with active regions harbouring complex sunspots, via isolated pores, down to the smallest yet resolved elements – so-called magnetic bright points (MBPs). Here, we revisit the various manifestations of solar magnetic fields by the largest European solar telescope in operation, the 1.5-meter GREGOR telescope. We show images from the High-resolution Fast Imager (HiFI) and spectropolarimetric data from the GREGOR Infrared Spectrograph (GRIS). Besides, we outline resolved convective features inside the larger structures – so-called light-bridges occurring on large to mid-sized scales.

Keywords. Sun: sunspots, Sun: magnetic fields, Sun: photosphere, Sun: chromosphere, instrumentation: high angular resolution

1. Sunspots – the large building blocks of solar magnetism

The most obvious and impressive solar magnetic features are sunspots. They are known to humans and observed at least since the ancient times (e.g., by ancient Chinese astronomers). Detailed observations started with Galileo Galilei in the Renaissance. Hale (1908) first discovered that sunspots are actually formed by strong magnetic fields and he identified the line splitting in sunspots caused by the Zeeman effect. In Figure 1, we show sunspots observed in 2017 during an observation campaign using the 1.5-m GREGOR telescope (Schmidt *et al.* 2012) with its powerful adaptive optics system (Berkefeld *et al.* 2012). On the left side, we see the simple active region NOAA 12681 consisting of a single sunspot showing a well-evolved penumbra around its umbral core. On the right panel of Figure 1 and in Figure 2, active region NOAA 12682 can be seen on September 29 and 28. This active region is strongly evolving and showing particularly

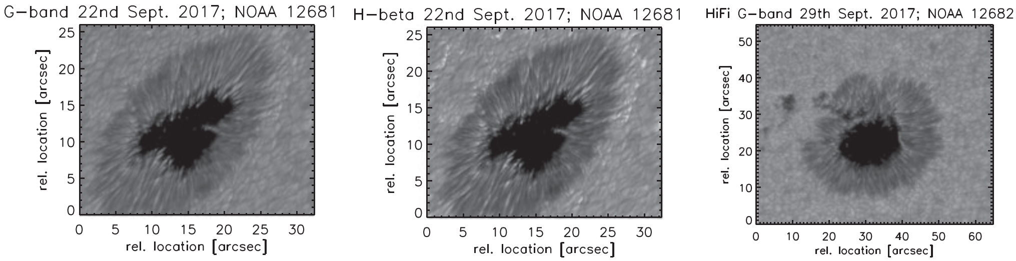

Figure 1. Sunspot in active region NOAA 12681 observed by HiFI (see, Denker *et al.* 2018) after speckle restoration. The left panel shows the G-band image, a magnetic field sensitive photospheric molecular band whereas the middle panel shows the same sunspot at the same time but observed by a broad-band filter centered at the Hβ line. This line is more sensitive to the chromospheric network and thus outlining better small-scale magnetic fields. The right panel shows a G-band image of the next appearing, more complex, sunspot in active region NOAA 12682.

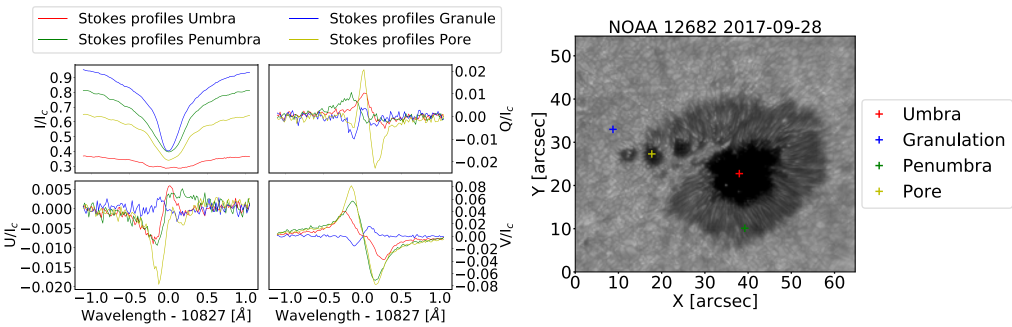

Figure 2. Active region NOAA 12682 (see, Figure 1, rightmost panel, but on the previous day). The right illustration depicts a HiFI speckle restored G-band image of the sunspot. The left panels illustrate Stokes spectra of a few selected pixels marked in the right panel observed by GRIS (Collados *et al.* 2012). Clearly, the penumbra substantially evolved by losing the pores within the penumbra while enclosing the whole sunspot within 24 hours.

interesting features like pores within the not yet closed and still evolving penumbra. The pores within the penumbra of September 28 (Figure 2, right panel) practically disappeared on September 29 (Figure 1, right panel). Besides, the penumbra starts to enclose more and more of the sunspot as it grows in the gap observed on September 28.

2. Features within sunspots

The two main features of sunspots are the central umbra and the surrounding filamentary penumbra. In addition, sunspots often display complex fine and small-scale structures. Among them are (see Figure 3 and, for example, Rimmele 2008):

– Umbral dots, i.e., small-scale convective features in the umbra where the convection is not fully suppressed by the strong magnetic fields and hot plasma can rise to the surface, and

– Light-bridges, i.e., regions of convection separating umbral cores (see Figure 3). Typically, they indicate the boundary of stronger flux elements (i.e., that the umbra of a sunspot can be formed by several strong magnetic centres and/or elements) and are often seen towards the end of the lifetime of a sunspot indicating the starting point of the terminal decline.

– Orphan penumbrae, i.e., regions of strong horizontal magnetic fields similar to normal penumbrae, but missing the umbra of a sunspot.

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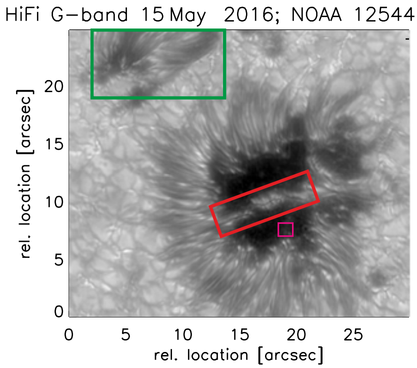

Figure 3. High-resolution HiFI speckle-restored G-band image depicting a complex sunspot (NOAA 12544) with a light-bridge (*red-box*), umbral dots (*pink-box*), and an orphan penumbra (*green-box*). Data courtesy of S. P. Rajaguru. More details of this region can be found in Felipe *et al.* (2017).

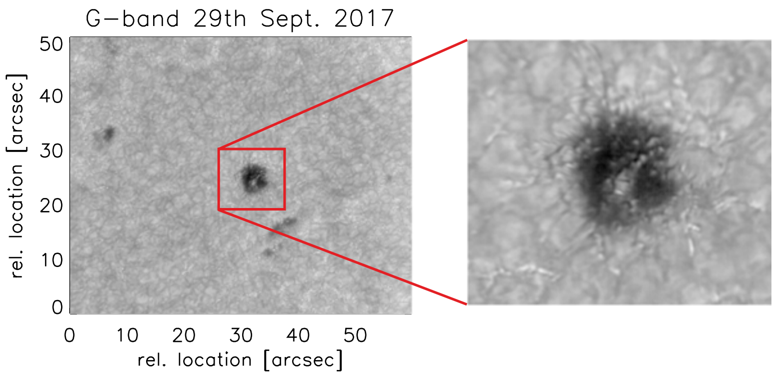

Figure 4. High resolution HiFI speckle-restored G-band image showing a strongly evolving pore. The left-hand side presents the full field-of-view within an emerging flux region. A region-of-interest is marked by a red square and a zoomed image is shown in the right panel. The pore is strongly evolving and exhibits a light-bridge on September 29 before dissolution. This light-bridge is evolving because of magneto-convection as is already evident on September 28 in Figure 5.

3. Pores and single flux fibers – the smaller building blocks

Solar magnetic fields are organised on many scales. Mid-sized magnetic features are pores, which generally consist of a strong vertical magnetic field in the absence of a penumbra (strong horizontal fields). In Figure 4, we show a pore observed on September 29. This particular pore showed an evolving light-bridge between September 28 and 29. Light-bridges are common features for sunspots often signaling their decay. Indeed, this pore disappeared on (or before) September 30. Figure 5 depicts the pore on September 28 as well as the smallest yet detectable solar magnetic features – so called MBPs (see, e.g., Utz *et al.* 2014; Kuckein 2019).

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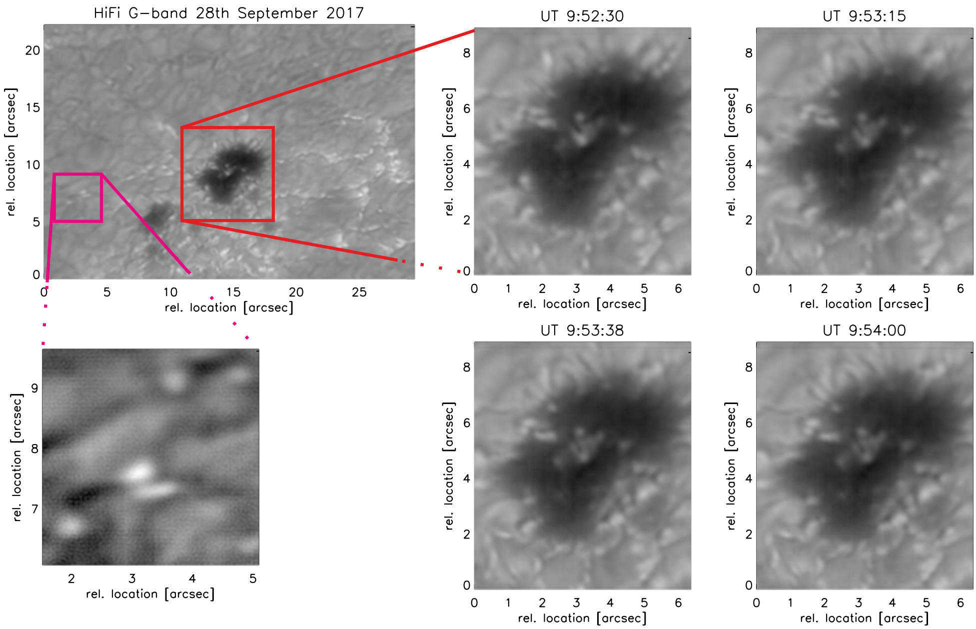

Figure 5. The same pore as in Figure 4, but one day earlier observed on September 28. Magneto-convective features can be seen in the centre of the pore. Magneto-convection is probably taking part at the boundary of stronger flux elements. This pore apparently consists of at least three monolithic magnetic flux elements. Probably the forces, which earlier brought the strong flux elements together, are weakening and magneto-convection can set in between the magnetic entities leading ultimately to the formation of the light-bridge (September 29; Figure 4) and the dissolution of the pore within the next 48 hours. The lower left close-up shows MBPs – currently the smallest detectable magnetic features.

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