Vigorous convection in a sunspot granular light bridge

Andreas Lagg\textsuperscript{1}, Sami K. Solanki\textsuperscript{1,2}, Michiel van Noort\textsuperscript{1}, and Sanja Danilovic\textsuperscript{1}

\textsuperscript{1} Max Planck Institute for Solar System Research, Justus-von-Liebig-Weg 3, 37077 G"ottingen, Germany
\textsuperscript{2} School of Space Research, Kyung Hee University, Yongin, Gyeonggi 446-701, Republic of Korea

e-mail: [lagg;solanki;vannoort;danilovic]@mps.mpg.de

Received 25/04/2014; accepted 20/06/2014

ABSTRACT

\textbf{Context.} Light bridges are the most prominent manifestation of convection in sunspots. The brightest representatives are granular light bridges composed of features that appear to be similar to granules.

\textbf{Aims.} An in-depth study of the convective motions, temperature stratification, and magnetic field vector in and around light bridge granules is presented with the aim of identifying similarities and differences to typical quiet-Sun granules.

\textbf{Methods.} Spectropolarimetric data from the Hinode Solar Optical Telescope were analyzed using a spatially coupled inversion technique to retrieve the stratified atmospheric parameters of light bridge and quiet-Sun granules.

\textbf{Results.} Central hot upflows surrounded by cooler fast downflows reaching 10 km s\textsuperscript{−1} clearly establish the convective nature of the light bridge granules. The inner part of these granules in the near surface layers is field free and is covered by a cusp-like magnetic field configuration. We observe hints of field reversals at the location of the fast downflows. The quiet-Sun granules in the vicinity of the sunspot are covered by a low-lying canopy field extending radially outward from the spot. The similarities between quiet-Sun and light bridge granules point to the deep anchoring of granular light bridges in the underlying convection zone. The fast, supersonic downflows are most likely a result of a combination of invigorated convection in the light bridge granule due to radiative cooling into the neighboring umbra and the fact that we sample deeper layers, since the downflows are immediately adjacent to the slanted walls of the Wilson depression.

\textbf{Conclusions.} The central upflows and, in particular, the fast downflows at the edges of granular cells directly adjacent to sunspot umbrae have already been observed by Shimizu et al. (2008a). The chromospheric activity above light bridges is often enhanced and manifests itself in the form of jets, surges, and brightenings in, say, C\textalpha\,H (Shimizu et al., 2009). Apart from these dynamic events, the magnetic field configuration in the upper chromospheric layers becomes very similar to the umbral environment (R"uedi et al., 1995b; Joshi, 2014).

The mechanism producing granular light bridges is believed to be distinctively different from the formation of other convective phenomena in sunspots like penumbral filaments or umbral dots. Whereas the latter are believed to be the consequence of magneto-convection within a 1–2 Mm thick layer below the photosphere (Sch"ussler & V"ogler, 2006; Rempel et al., 2009a, b), thicker light bridges are attributed to intrusions of field-free plasma from deep beneath sunspots (Rempel, 2011; Leka, 1997) or to the inward motion of hot gas from the penumbra triggered by sub-photospheric flows crossing the sunspot (Katsukawa et al., 2007). Broad light bridges often consist of several granular convection cells along the light bridge axis. The presence of such granulation cells embedded in the low-density, transparent environment of sunspot umbrae and the resulting exposure of their walls allow probing the physical conditions in

Send offprint requests to: A. Lagg, e-mail: lagg@mps.mpg.de

\textbf{Key words.} Sun: sunspots, Sun: photosphere, Sun: granulation, Sun: magnetic fields, Techniques: polarimetric
deep layers of such cells, which are otherwise not accessible to direct observation.

This possibility motivated us to investigate the properties of granular light bridges based on the physical parameters determined from spatially coupled inversions of Hinode spectropolarimetric data. The observations and the analysis method are described in Sections 2 and 3, respectively. We present the properties of light bridge granules in Sec. 4 and compare these with their quiet-Sun counterparts. We then discuss the observed configuration in Sec. 5 and summarize the results in Sec. 6.

2. Observations

Spectropolarimetric data of the leading spot of AR10926 were obtained using the spectropolarimeter of the Hinode Solar Optical Telescope (SOT/SP, Kosugi et al., 2007; Tsuneta et al., 2008; Suematsu et al., 2008; Ichimoto et al., 2008; Shimizu et al., 2008b; Lites et al., 2013) on November 30 2006 UT 23:40–00:05. The center of the analyzed region was located at the solar position \( \alpha = -184^\circ, \beta = -160^\circ \), corresponding to a heliocentric angle of \( \Theta = 14.5^\circ \) (\( \mu = \cos \Theta = 0.97 \)).

SOT/SP was operated in “normal map” mode with a pixel size of 0′′16 in both, the slit and the scan direction. The exposure time per slit was 4.8 s, resulting in a noise level in the quiet-Sun obtained using the Hinode SOT Broad-band Filter Imager (BFI) at the time of the SOT SP observation on the interpolated grid (pixel size 0′′08, see Sec. 3. AR10926 came across the east limb on November 24 2006 SOHO/MDI images indicate that already then the sunspot umbra was divided into several unipolar regions separated by strong light bridges. The decaying sunspot disappeared behind the west limb on December 8. The segmentation of the umbra into 3–6 parts separated by strong, granular light bridges could be observed from November 26 until December 4, indicating that the sunspot structure presented in Fig. 1 represents a quite stable configuration (see the animation attached to Fig. B.1). The temporal evolution of the sunspot obtained using the Hinode SOT Broad-band Filter Imager (BFI) at the time of the SOT/SP scan in G-band (left) and Ca ii H (right) is attached to Fig. B.2. These movies indicate that there was no enhanced activity, beyond what is normal for the immediate surroundings of sunspots, visible above the light bridges, neither in the G-band nor in the Ca ii H line. Note the dark lines running roughly along the middle of some of the light bridges in the Ca ii H movie. The LOS velocity map, resulting from the inversion described in Sec. 3 (right panel), nicely illustrates the strong downflows all along the edges of the granular light bridges.

The inset (B1) in Fig. 1 shows a typical “granular” cell within a granular light bridge. We name these cells “light bridge granules” (LBGs). Several dark lanes can be identified in the continuum image indicating a lower temperature at the \( r = 1 \) layer. In this study, we compare the properties of several such LBGs with those of “plage granules” (PtGs) and “quiet-Sun granules” (QSGs) found in the same data set, typical examples of those are shown enlarged in boxes (B2) and (B3) of Fig. 1, respectively. The analyzed PtGs are located approximately 5′–10′ away from the visible penumbra boundary, the region for the QSGs lies approximately 20′–30′ north of the penumbral boundary (note the break in the \( \gamma \)-axis in Fig. 1), where the weakly polarized Stokes profiles indicate an area of very low magnetic field.

3. Analysis method

3.1 Maps of atmospheric parameters

The temporal evolution of AR10926 (see online material) indicates the convective nature of its light bridges. The long axis of each light bridge consists of a chain of convective cells with widths typical of quiet-Sun granules (1′–2′). The atmospheric...
Fig. 1. Continuum map of AR10926 composed from the fitted Stokes I profiles (left) and LOS velocity map at log $\tau = 0.0$ (right). Positive values (red/yellow colors) denote downflows. The direction toward the disk center (DC) is indicated by the black arrow. The boxes ($B1$, $B2$, and $B3$) and the lines ($C1$ in the center), ($C2$) (top left), and ($C3$) (top center) correspond to regions analyzed in Sec. 4. The red, cyan, and yellow crosses in the continuum image mark the granules used to determine the average atmospheric parameters in Tab. 1 for LBGs, PtGs, and QSGs, respectively.

parameters derived from the inversions of the Stokes parameters allow us to confirm and to characterize the convective nature of these cells. As an example, in Fig. 2 we present maps of the temperature, LOS velocity, and the strength and direction of the magnetic field for the three log $\tau$ nodes used during the inversion of a typical LBG.

The temperature and the LOS velocity maps of the LBG (first two columns in Fig. 2) show clear evidence for convection: a central upflow of hot material in the deepest layer (bottom row) is surrounded by a downflow of cooler material. With increasing height the granular interior cools down more rapidly than the surrounding, giving the impression of reversed granulation in the highest layer (e.g., Cheung et al., 2007). The magnitude of both, up- and downflow velocities decreases with height. This general pattern is very similar to that of “normal” granules, located in plage and quiet-Sun regions (PtGs and QSGs), presented in Fig. 3 and Fig. 4, respectively.

We note that the values of the physical parameters for the “normal” granules in plage and quiet-Sun regions (PtGs and QSGs) are very similar and show the typical signatures of convective cells. Temperature and $v_{\text{LOS}}$ stratification in PtGs and QSGs are almost indistinguishable and show the expected properties of a central upflow, decreasing in magnitude with height, surrounded by downflows in the intergranular lanes, with the highest velocities in the deepest layer. The magnetic properties of PtGs and QSGs differ only in two aspects: The boundaries of PtGs show magnetic field strengths that are significantly increased, typically by a few hundred Gauss at the resolution of these data, and the interior of PtGs shows an enhanced horizontal magnetic field in the top layer. In contrast, the QSG shows a field-free interior at all heights and only weak fields of on average 100 G in the deepest layer of the intergranular lane. The PtGs do appear to be smaller, on average, than the QSGs.

In spite of the general similarity, there are significant differences between the LBGs, on the one hand, and the QSGs and
Fig. 2. Light bridge granule (LBG, inset (B1) in Fig. 1): Plotted are from left to right: temperature $T$, LOS velocity, magnetic field strength $B$, and inclination $\gamma$ (color scale) of the magnetic field to the LOS for the three log $\tau$ nodes used in the inversion (from top to bottom). The azimuth is overplotted as white lines on the inclination plots (rightmost panels). Inclination and azimuth lines are only plotted for $B > 70 \text{ G}$. The black contour lines enclose regions of LOS velocities greater than $3 \text{ km s}^{-1}$ in the deepest layer.

Fig. 3. Same as Fig. 2 for a plage granule (Pt.G, inset (B2) in Fig. 1). The same color scales were chosen as in Fig. 2 to facilitate comparison.

Fig. 4. Same as Fig. 2 for a quiet-Sun granule (QSG, inset (B3) in Fig. 1).

Table 1. Average atmospheric parameters for the interiors and the boundaries of several LBGs, Pt.Gs, and QSGs.

| Parameter | Interior | Boundary |
|-----------|---------|----------|
| $T$ [K]   | 4810    | 4980     |
| $B$ [G]   | 5330    | 5550     |
| $\gamma$ [$^\circ$] | 108 | 129     |
| $v_{\text{LOS}}$ [km s$^{-1}$] | 120 | 142     |

Each, marked with the red, cyan, and yellow crosses in Fig. 3. The interiors of granules are defined as the regions where the three height layers show upflows, in order to reflect the shrinking of especially the LBGs with height. The boundary regions are defined using the fast downflow regions in the deepest layer.

The most striking difference in Tab. 1 is the downflow velocity in the lowest layer ($\log \tau = 0$). These averaged downflows in LBGs are more than a factor of 2 larger than those in the “normal” granules. The same is true for the maximum downflow velocities at the boundaries of the LBGs, which reach values of $10 \text{ km s}^{-1}$ compared to the maximum values of $3–4 \text{ km s}^{-1}$ in the darkest parts of the intergranular lanes of “normal” granules. The average temperature in the LBGs at the location of these fast downflows ($\log \tau = 0$) is similar to the average temperatures at the boundaries of Pt.Gs and QSGs, but is on average $140–250 \text{ K}$ higher in the middle layers (at $\log \tau = -0.8$). The temperature in the center of the LBG is lower than in the Pt.G, with an increasing difference of $\approx 140 \text{ K}$ to $\approx 220 \text{ K}$ from the top to the bottom layer. This leads to the interesting feature that the radial temperature profile in the deepest layer of LBGs, i.e. the temperature difference between the granular interior and the boundaries, is
rather flat ($\approx 300$ K difference) whereas in the “normal” granules the interior is significantly hotter than the intergranular lanes. The central upflow above the LBG narrows with height to form a thin, elongated sheet parallel to the light bridge axis. In contrast, the shape of the upflow region in P$_{\delta}$Gs and QSGs remains unchanged with height. The upflow velocities in the interiors at all heights are comparable, reaching maximum values of $\approx 2$ km s$^{-1}$ in the deepest layer and 1 km s$^{-1}$ in the top layer.

A striking common feature in the magnetic field strength maps (3$^{rd}$ column of Figs. 2–4) is the almost complete absence of a magnetic field in the middle and bottom layer of the cellular interior in all three types of granules. For the LBG, a sharp transition exactly at the outer edge of the fast downflows separates these field-free regions from the umbral field with strengths of more than 2 kG at log $\tau = 0$. The top layer of the LBG already exhibits field strengths close to one kG, with lower field strengths of $\approx 200$ G within the elongated upflow region. In combination with the magnetic field orientation presented in the inclination maps (4$^{th}$ column of Fig. 2) the picture of a cusp-like field configuration closing above the field-free region in the middle to upper photosphere becomes evident. The dark lines overlaying the light bridge harboring this LBG in the Ca I H movie provides further support for this picture. The temperature is lower at the upflow at log $\tau = -2$ in the LBG, whereas it is relatively flat in the other granules. This is consistent with the presence of a cusp in the field above the upflow lane, so that we see higher and cooler layers there.

A hint of opposite polarity field is present in the inclination maps in the middle and deepest layers of LBGs, located at the innermost boundary of the fast downflows. These opposite polarity fields are very weak. It is therefore difficult to judge how trustworthy their presence is. However, it should be noted that these weak, opposite polarity fields are present at the same location in all LBGs investigated in the course of this study, irrespective of their orientation.

The magnetic field in the plage and the quiet-Sun is concentrated in the intergranular lanes, where it reaches kG and hG values (Lagg et al., 2010), respectively (see Figs. 3 and 4). In the highest layer the field strength in the PlG above the field-free granular interior is slightly above the detection threshold of $\approx 50$ G (for horizontal fields). There the field is mainly horizontal and shows a clear preferred orientation toward the spot. This configuration is consistent with a low lying sunspot canopy field extending radially away from the sunspot outside the visible sunspot boundary (Giovanelli, 1980; Giovanelli & Jones, 1982; Solanki et al., 1992, 1994, 1999; Buehler et al., 2014). In contrast, the interior of QSGs is field-free at all heights.

The fast downflows of up to 10 km s$^{-1}$ at the edges of LBGs in the deepest layers suggest that these flows are supersonic. To verify this we compute the Mach number $M = v/c_s$, using the thermodynamic parameters gas pressure, $p$, and density, $\rho$, provided by the inversion for every pixel and height grid point in our maps. The equation of state look-up tables from the radiative magneto-hydrodynamic (MHD) code MURaM (Vögler et al., 2005) are used to compute the sound speed in the general form

$$c_s = \sqrt{\frac{\partial p}{\partial \rho}}$$

where the partial derivative is taken adiabatically, i.e. at constant entropy $S$. The MURaM tables take into account the effects of partial ionization. We use $v_{\text{los}}$ to compute a lower limit of the Mach numbers presented in Fig. 5 for the LBG (top row, box (B1)) in Fig. 1 and the QSG (bottom row, box (B3)). Since the very high speed downflows are concentrated only in the deepest layers of the photosphere, the Mach number maps are only shown for log $\tau = [-0.4,-0.2,0.0,0.2]$ (from left to right). The maps nicely illustrate that in the deep-
the downflows are clearly visible in the inclination map (bottom panels).

Fig. 7 and 8 show a vertical cut through a PtG and a QSG (cut (C2) and (C3) in Fig. 1) each. Similar to the LBG, the central upflow, surrounded by the downflows in the intergranular lanes, nicely outlines the convective motion in the granule. In contrast to the LBG, the temperature at the boundary of the granule (the intergranular lane) is lower than the averaged quiet-Sun temperature profile. The magnetic field of the PtG is concentrated in the highest layer, where it shows a horizontal, low-lying canopy configuration.

5. Discussion

It was shown in Sec. 4 that the atmospheric conditions in the lower layers of the LBG interior are qualitatively similar to the interior of “normal” granules in plage and quiet-Sun regions. This suggests a common origin for the convective motion creating these cells, which for the granulation pattern in the quiet-Sun is known to be a result of the cooling and hydrogen recombination within the plasma parcels when they reach the low opacity layer of the solar surface. Unlike the surface convection responsible for umbral dots and faint light bridges, which takes place in a 1–2 Mm thick layer immediately below the solar surface (e.g., Schüssler & Vögler, 2006), the convection cells responsible for granular light bridges are rooted deeper in the underlying convection zone (Rempel, 2011). This interpretation is supported by the near absence of magnetic field in the interior of the LBGs (see also Sobotka et al., 2013), distinctly different from the significant field strengths measured in the deep layers of umbral dots, which is lower by only \( \approx 500 \) G than in the surrounding umbra (Riethmüller et al., 2013). These field-free regions are only found in the interiors of granular LBs. Narrower LBs however, harbor hecto-Gauss fields in their interior (Jurčák et al., 2006).
Another indication for the deep anchoring of granular light bridges is their long-term stability. SOT/BFI observations demonstrate, that the granular light bridges in the active region studied here appeared already 4–5 days before the presented SOT/SP scan and lasted another 4–5 days after this scan, until the sunspot finally started to decay (see the animation attached to Fig. B.1). Granular light bridges are therefore likely to be real gaps in the subsurface magnetic environment. According to Rempel (2011), such gaps may be the result of fragmentation events, where field-free plasma intrudes the magnetic root of the sunspot several Mm below the solar surface. In his magnetohydrodynamic simulations, such intrusions become visible in the photosphere after timescales of several hours to one day. An alternative possibility is that LBGs are found at the boundary between fragments that emerged individually and then joined to form the sunspot (Garcia de La Rosa, 1987).

The differences between LBGs and “normal” granules are clearly dominated by the special location where the upward moving gas reaches the photosphere. The LBGs are exposed to the cold, strongly Wilson-depressed umbral environment, where they stick out like a few-hundred-kilometer-high mountain ridge crossing the umbra (Rüedi et al., 1995a; Lites et al., 2004). The downflow velocities of up to 10 km s\(^{-1}\) at the boundaries of this ridge can be explained by a combination of gravitational acceleration and the efficient radiative cooling toward the cold umbral environment. This cooling causes the gas to sink faster, in effect making the convection more vigorous. Another reason for the strong observed downflows in LBGs is that we see these downflows at geometrical heights significantly deeper than the downflows in normal intergranular lanes. This is caused by the inclined walls of the umbra as the magnetic field expands with height (and decreasing gas pressure), directly visible in the vertical cut plotted in Fig. 6. Since granular downflows tend to accelerate with depth, at least for the first few 100 km, this view into deeper layers also tends to show stronger downflows. As already stated by Shimizu (2011), a reconnection mechanism, as proposed by Louis et al. (2009), is not required to produce these downflows.

Fig. 5 demonstrates that the gas flows in the deepest layer of the edges of LBGs are supersonic. The possible existence of transonic fluid velocities was postulated by Cattaneo et al. (1990) and Malagoli et al. (1990) using numerical simulations of convection. An important ingredient to these flows are non-adiabatic effects caused by the radiative losses in this layer, causing the temperature and subsequently the sound speed to decrease significantly and therefore to accelerate the pressure gradient driven, initially horizontal flow to transonic speeds near the edges of granules. Such horizontal supersonic flows have been detected in observations (Solanki et al., 1996; Rybak et al., 2004; Bellot Rubio, 2009), but this is the first time that granulation with supersonic downflows is reported. In the case of the elevated LBG discussed here, the radiative losses do not act on the horizontal flows above the granule interior, but continue to be an efficient, non-adiabatic process lowering the temperature as the gas flows down the slanted walls of the LBG. This process, in combination with the gravitational acceleration, provides a natural explanation for the supersonic flow speeds observed at the edges of LBGs. The temperature of the downflowing material is determined by multiple effects. On the one hand, it is lowered by radiative cooling, both into space and into the neighboring cold umbra. On the other hand, the deeper layers are hotter due to the general increase of temperature with depth. The balance between these two effects results in temperatures of the visible downflowing gas that are rather similar to the upflowing gas in the lower photosphere (see Fig. 2), in contrast to a PtG or QSG (see Fig. 3 and 4).

The observed downflows occur in a regime where the kinetic energy dominates over the magnetic energy, i.e., where the magnetic field strength is below the equipartition field strength (\(B_{\text{eq}} = v \sqrt{\mu_0 n} \), with \(v\) being the typical velocity of motion and \(\mu_0\) the magnetic permeability). As a consequence, the downflowing material is able to drag the outermost umbral magnetic field lines down and bend them back into the solar interior. This scenario is illustrated in the sketch in Fig. 9. The magnetic field configuration determined from the inversion is compatible with two different scenarios: The tension of the magnetic field is high enough to allow the field line to reverse its direction again (left-hand side of Fig. 9), or the field is dragged down and eventually probably “shredded” in the convective motions in the granule interior (right side of Fig. 9). The opposite polarity field measured at the inner edge of the fast downflows provides evidence for these scenarios. In both cases, the opposite polarity field, confined to a narrow layer, may dissipate a part of its energy, indicated by the yellow zig-zag line in Fig. 9. Magnetic energy can be released by either reconnection processes or by Ohmic dissipation of electric currents flowing in these narrow layers.

The apparent temperature enhancement directly above the fast downflow regions can be attributed to such a magnetically driven heating mechanisms only to a minor extent. As shown in online App. A one needs to dissipate \(\approx 500\) G in order to raise the temperature by \(\approx 100\) K at \(\tau \approx 1\). Due to radiative losses, this enhancement is soon removed, so that very significant amounts of magnetic flux would have to be constantly removed to achieve any measurable heating. The often observed enhanced chromospheric activity above light bridges in the form of jets and surges (e.g., Shimizu et al., 2009; Shimizu, 2011; Bharti et al., 2007) may, however, be the result of reconnection triggered by the reversal of the field caused by the downflowing material. Since no enhanced chromospheric activity was observed during the time
The transonic speeds of these downflows must unavoidably lead to the formation of shocks, when the flows encounter the high density, deep photospheric layers. The resulting shock waves could, outside the downflow channel, in principle propagate upward into the umbra and subsequently heat the layers above the downflows, explaining the observed apparent temperature enhancement. However, since the measured downflow speeds continue to increase with decreasing optical depth, the shock must be located in deeper layers not accessible by our observations. Therefore the energy deposited by this process is unlikely to reach the heights where we observe the apparent temperature enhancement.

Two other possible origins for this apparent temperature enhancement do not require a specific heating mechanism: Firstly, this enhancement could result from the energy radiated horizontally away from the, on a geometrical height scale elevated, slanted walls of the LBG into the umbra. Due to the decreasing size of the LBG with height the regions heated by this energy appear directly above the strong downflows in the deepest layer, where the granule is broadest. Secondly, the magnetic field in the downflow lanes of the LBG is stronger than in the other two granules studied here and in addition is inclined above the LBG (cusp shape), which decreases the effective gravity and increases the vertical scale height. The density is reduced by the magnetic field, resulting in a depression of the iso-τ surfaces to deeper, hotter layers. The increased vertical scale height along the field reduces the vertical temperature gradient, producing an apparent temperature enhancement as compared to the surrounding areas with weaker and more vertically oriented magnetic field. Since this effect is mainly produced by the height variation of the iso-τ surfaces, it may well be absent if geometric height coordinates would be used. However, the lack of knowledge about the true geometric height scale makes it difficult to estimate the significance of the above mentioned processes in producing this apparent temperature enhancement.

At higher layers above the LBGs, the expected cusp-like configuration of the magnetic field becomes clearly visible in the inversion results. The field reaches inclinations with respect to the umbral field of 70°, in good agreement with the value found by Scharmer et al. (2008) on a short, irregular light bridge. A narrow central upflow lane remains visible up to the log τ \(\approx -2.5\), i.e. the highest level reliably retrieved by inversions of the FeI 630 nm line pair. Since no continuous net upflow above light bridges is observed at chromospheric heights (Joshi, 2014), it is likely that at heights above the formation height of these FeI lines the upflowing material reverses its direction and contributes to the observed downflows.

The visual impression from the velocity maps in Fig. 2 suggests a significant excess of downflowing material over upflowing material. It is likely that this impression is a consequence of the fact that the up- and downflowing material is measured at different heights, with the downflowing material being sampled at deeper layers, and, because of the inclined iso-τ surfaces, over a range of heights. The corrugation of the log τ = 0 surface makes it virtually impossible to establish an overall mass flux balance. This problem may be solved in the future by stereoscopic measurements, e.g., by combining magnetic field maps obtained with the Solar Orbiter Polarimetric and Helioseismic Imager (Gandorfer et al., 2011) with ground-based or Earth-orbiting spectropolarimetric measurements.

### 6. Summary & Conclusion

We presented results from spatially coupled inversions of Stokes profiles in granular light bridges and in plage and quiet-Sun granules. A significant degree of similarity between light bridge granules (LBGs) and granules in plage and quiet-Sun regions (PGs, and QSs), especially in the deep layers of the cell interior, point to the common driving mechanism of the convective motions. The interiors of all three types of granules are void of measurable magnetic field in their deepest observable layers (τ \(\approx 1\)). The field-free regions are dominated by upflowing plasma with velocities of up to 2 km s\(^{-1}\). For LBGs, these upflows get squeezed in higher layers into narrow, thin sheets by the expanding magnetic field of the umbra on both sides of the LBGs. The magnetic configuration is consistent with a cusp overlying the upflow. The walls of the LBGs, exposed to the dark umbral environment, harbor downflows with velocities of up to 10 km s\(^{-1}\), exceeding the local sound speed in the deepest observable layers. Hints of field reversal are present in the vicinity of these downflows.

The similarity between LBGs and “normal” granules suggests that granular light bridges are anchored in deep layers. This distinguishes granular light bridges from other convective processes in sunspot umbrae, like umbral dots or faint light bridges, which are, according to MHD simulations, the product of surface magneto-convection within the 1–2 Mm just below the local solar surface.

The exposure of the walls of granular light bridges due to reduced opacity in sunspot umbrae offers an attractive way to probe the deep interior of convective cells using LBGs. A future analysis of LBGs under different viewing geometries, either by studying their center-to-limb variation or by performing stereoscopic measurements might help to uncover further details of the heat producing, or the study of flow geometry and magnetic field configuration on a geometrical height scale.

Acknowledgements. Hinode is a Japanese mission developed and was launched by ISAS/JAXA, collaborating with NAOJ as a domestic partner, NASA and STFC (UK) as international partners. Scientific operation of the Hinode mission is conducted by the Hinode science team organized at ISAS/JAXA. This team mainly consists of scientists from institutes in the partner countries. Support for the post-launch operation is provided by JAXA and NAOJ (Japan), STFC (U.K.), NASA, ESA, and NSC (Norway). This work was partly supported by the BK 21 plus program through the National Research Foundation (NSF) funded by the Ministry of Education of Korea. The development of the inversion code benefited from two meetings held in February 2010 and December 2012 at the International Space Science Institute (ISSI) in Bern (Switzerland) as part of the International Working Group “Extracting Information from Spectropolarimetric Observations: Comparison of Inversion Codes”.

References

Bellot Rubio, L. R. 2009, ApJ, 700, 284
Bharti, L., Hirzberger, J., & Solanki, S. K. 2013, A&A, 552, L1
Bharti, L., Rimmle, T., Jain, R., Jaafrey, S. N. A., & Smartt, R. N. 2007, Monthly Notices of the Royal Astronomical Society, 376, 1291
Biermann, L. 1941, Vierteljahresschrift der Astronomischen Gesellschaft, 76, 194
Buchler, D., Lagg, A., Solanki, S., & van Noort, M. 2014, A&A, in preparation
Buchler, D., Lagg, A., & Solanki, S. K. 2013, A&A, 555, A33
Cattaneo, F., Huruburt, N. E., & Toomre, J. 1990, ApJL, 349, L63
Cheung, M. C. M., Schüssler, M., & Moreno-Insertis, F. 2007, A&A, 461, 1163
Friiger, C. 2000, PhD thesis, ETH Zurich, Switzerland, Diss ETH No. 13896
Friiger, C., Solanki, S. K., Fligge, M., & Bruls, J. H. M. J. 2000, A&A, 358, 1109
Gandorfer, A., Solanki, S. K., Woch, J., et al. 2011, Journal of Physics Conference Series, 271, 012086
Garcia de La Rosa, J. I. 1987, Sol. Phys., 112, 49
Giovaneli, R. G. 1980, Sol. Phys., 68, 49

Andreas Lagg et al.: Vigorous convection in a sunspot granular light bridge
Fig. B.1. G-band images demonstrating the long-term stability of the LBGs under investigation in this paper. The animation, composed from G-band images of the Hinode SOT Broad-band Filter Imager (BFI), covers the time period from 2006-Nov-30, 07:40 UT until 2006-Dec-03, 23:59 UT. The same granular light bridges are present from the beginning of the observations until the end. The movie is also available on the MPS website: http://www.mps.mpg.de/homes/lagg/OnlineMaterial/2014_LightBridge/gband_gap.avi.

Appendix A: Temperature increase due to magnetic field dissipation

As stated in Sec. 5, the enhanced temperature observed directly above the regions of fast downflows at the edges of LBGs can only to a minor extent be attributed to magnetically driven heating mechanisms. To demonstrate this, we compute here the maximum possible temperature increase ($\Delta T$) by completely dissipating a magnetic field ($B$) with a given magnetic energy density ($\rho_M = B^2/2\mu_0$) under typical photospheric conditions:

$$\Delta T = \frac{Q}{c} = \frac{c}{c_{\text{mol}}}$$

(A.1)

with $Q$ being the thermal energy, $c$ the heat capacity, $n$ the amount of gas in moles, and $V$ the volume. For simplicity we assume a 1-atomic, ideal gas ($c_{\text{mol}} = \frac{5}{2}R$) to compute $Q$:

$$Q = V\rho_M = V\frac{B^2}{2\mu_0} = \frac{nRT}{p} \frac{B^2}{2\mu_0}$$

(A.2)

(with $R$ = universal gas constant, $p$ = gas pressure, and $T$ = temperature). By inserting this into Eq. A.1 we can compute $\Delta T$:

$$\Delta T = \frac{2}{3} \frac{T}{p} \frac{B^2}{2\mu_0}$$

(A.3)

Using typical atmospheric conditions in a sunspot from the umbra model of Maltby et al. (1986) at $\tau = 1$ ($p = 2 \cdot 10^5$ dyn/cm$^2$, $T = 3500$ K) we obtain a temperature increase of $\Delta T = 18.5$ K for $B = 200$ G, and $\Delta T = 116$ K for $B = 500$ G.

Appendix B: Animations