Interaction of horizontal vortex tubes with magnetic fields

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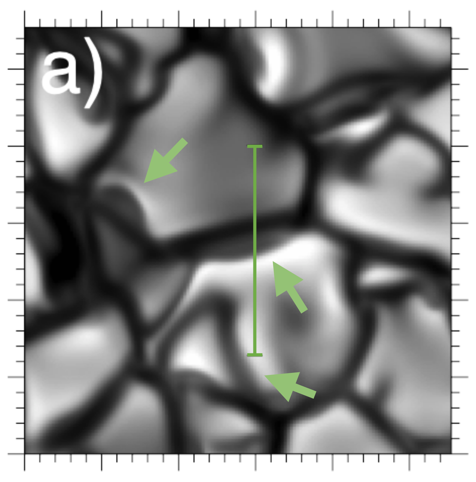
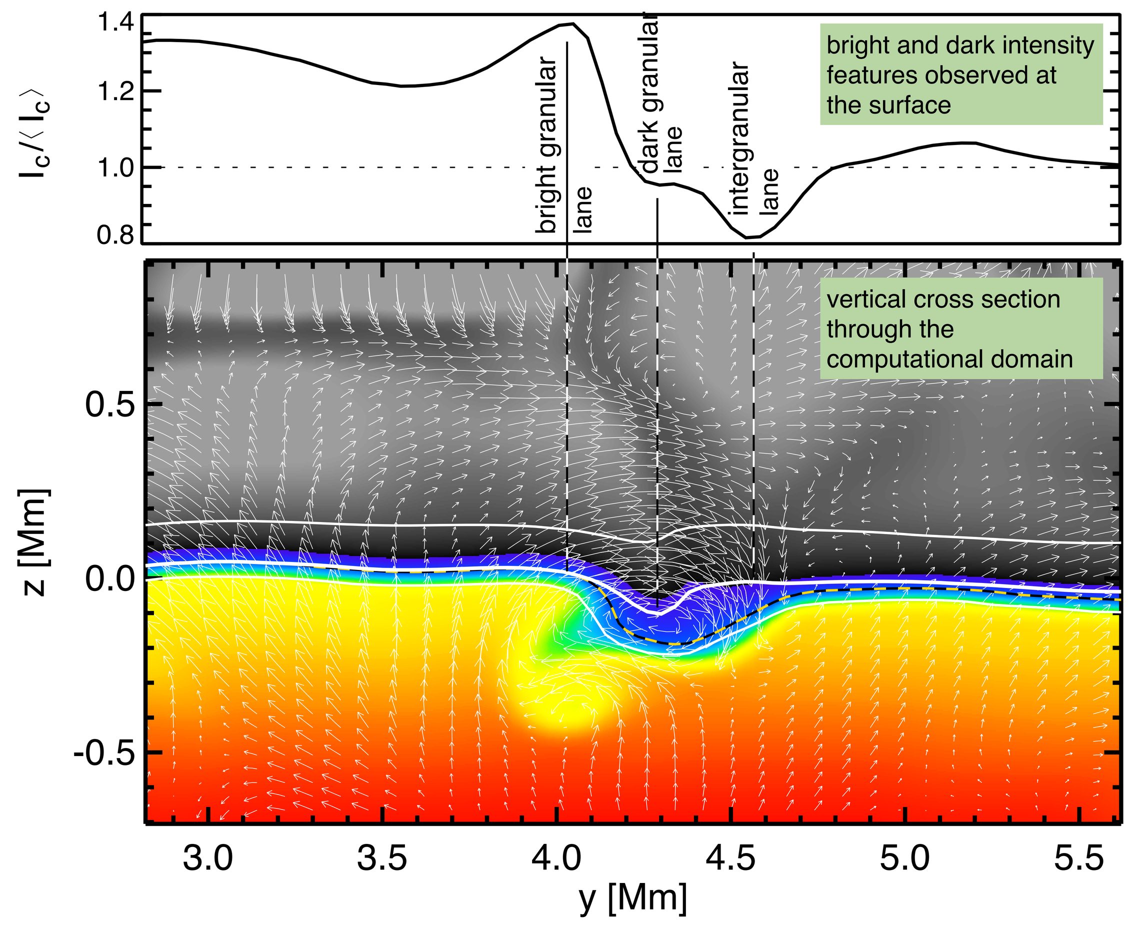


Modified figure from Steiner et al., 2010, ApJL, 723, L180

A large number of granules exhibit a distinct feature - the so-called granular lanes (GLs). This feature presents as a bright rim followed by a dark archlike lane traveling into the host granule. Figure (a) on the left shows a synthesised figure of the continuous radiation with a field-of-view of 5.3 Mm x 5.3 Mm. The arrows point to several granular lanes. After traveling into the granule the GLs then either disappear within the granule, or retract back to the granule boundary from where they had started from.

With the help of 3-D magnetohydrodynamic simulations Steiner et al. (2010) found that this intensity pattern is the visible signature of a subsurface velocity vortex tube.

In figure (b) a cross section of the solar atmosphere and the subsurface along the green vertical line across a GL indicated in figure (a) is shown. The colors indicate temperature and arrows indicate the velocity field. The white contours indicate optical depths of τ= 0.1, 1.0, and 10 from top to bottom. The velocity arrows show a vortex, with its axis piercing through the viewing plane at around (y,z) = (4.3, -0.15)[Mm]. The longest arrows correspond to a velocity of 8.5 kms^{-1}. (Adapted from Steiner et al., 2010)



Adapted from Steiner et al., 2010, ApJL, 723, L180

Observations

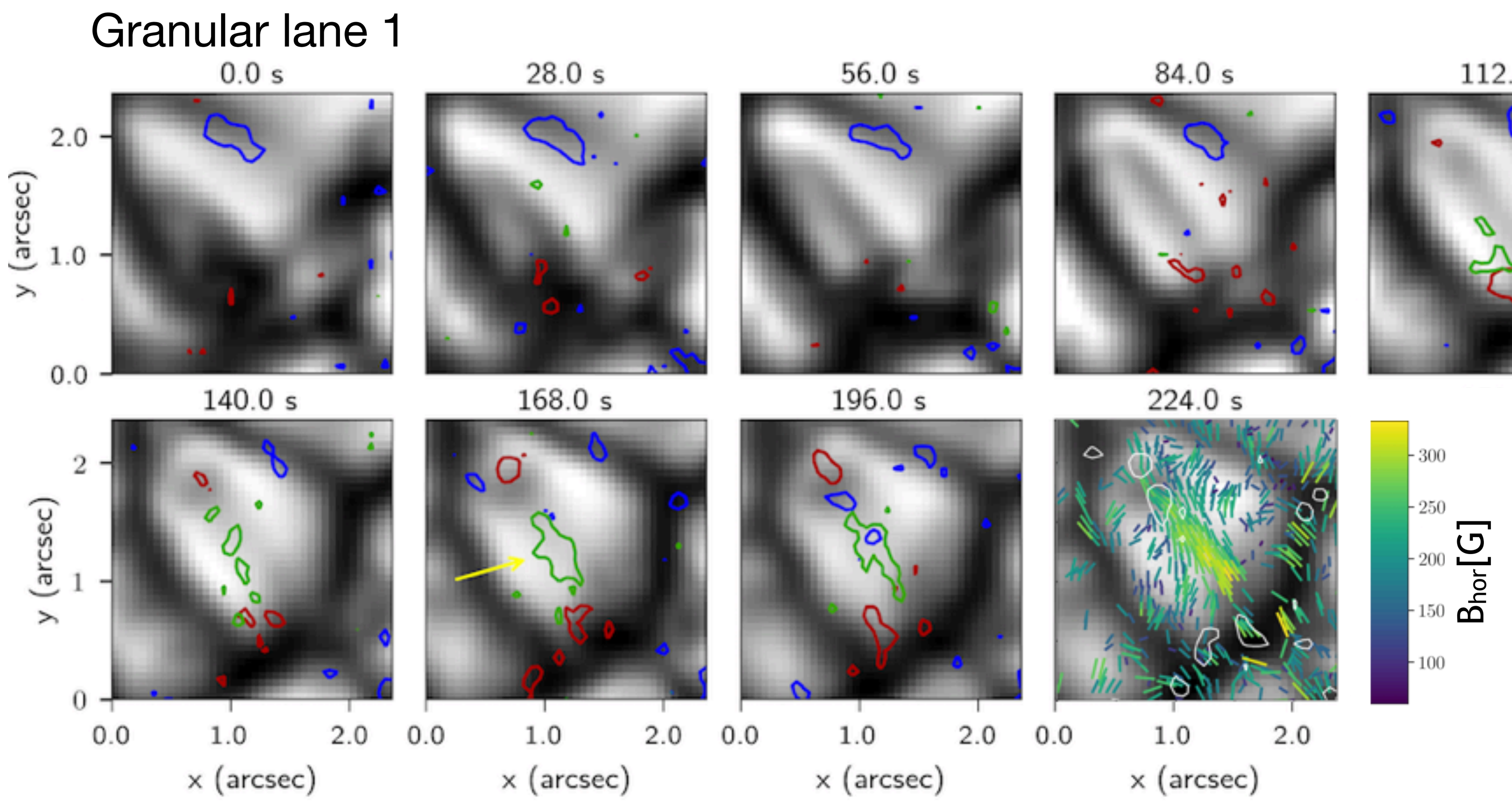
CRISP/SST

- SOLARNET ACCESS time
- quiet-Sun at disk center
- Field-of-view 50" to 50"
- Cadence about 28 s, 2 h series
- pixel size about 0.059"
- Fe I 6173 Å full Stokes

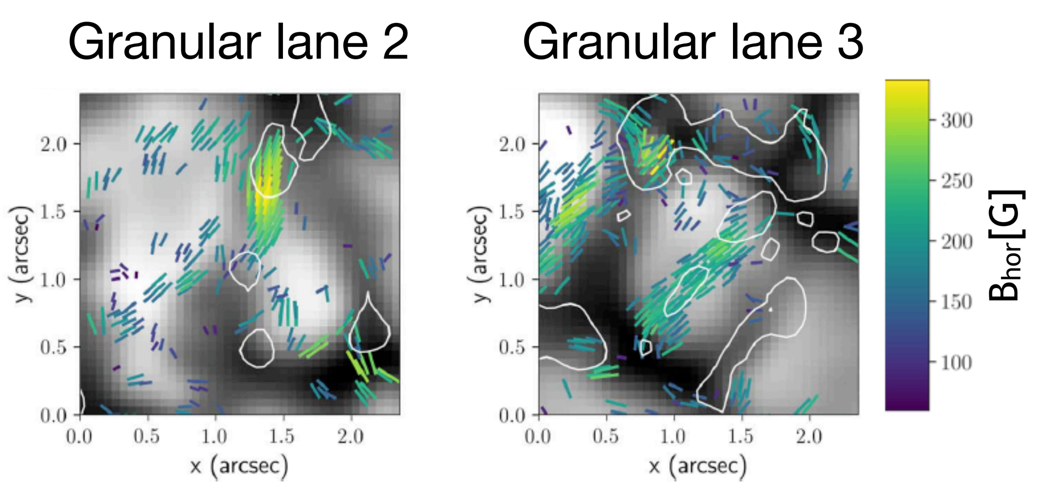
Simulations

CO⁵BOLD

- Field-of-view 9.6Mm x 9.6Mm x2.8Mm
- Cadence about 10s, 60 snapshots
- Grid size 10 km



The sequence of maps on the left shows the continuum intensity close to the Fe I 617.3 nm line. Green contours denote the linear polarization, whereas red and blue mark positive and negative circular polarization. The yellow arrow points to the location where the dark component of the granular lane is occupied by a substantial patch of linear polarization. The panel at t=224 s indicates the direction of the horizontal magnetic field as calculated through VFISV (Borrero et al., 2011) Stokes inversions. We plot the horizontal magnetic field only at those locations where the signal in either Stokes Q or U is larger than three times the noise level. (Adapted from Fischer et al., 2020)



We observe a similar scenario with GL2 and GL3 shown in the left figure with the direction of the horizontal magnetic field again indicated by strokes. In each case, the polarization develops at a later stage of the granular lane evolution when the dark lane already fades. Here too, we find elongated linear polarization patches aligned with the direction of the dark lane and flanked by circular polarization patches of opposite polarity at the two ends of the dark granular lane. In both cases the surrounding intergranular lanes already harbored some preexisting circular polarization signal, probably not connected to the GL. The same goes for GL3 where the emerging flux shows a more complex configuration. In all three cases, the horizontal magnetic field is aligned with the dark granular lane reaching a field strength (B_{hor}) of up to 300 G.

The appearance of magnetic field in connection with granular lanes led us to investigate where these fields come from and how they emerge. By studying simulations performed with the CO⁵BOLD code, we showed that vortex tubes can drag magnetic field from intergranular lanes into granule interiors and let them re-emerge into the solar atmosphere (see figure below on the right). The magnetic field showed several components (lane-aligned, twisted, or turbulent fields) dominating in different stages of the process and revealing a complex magnetic structure.

Summary and Outlook

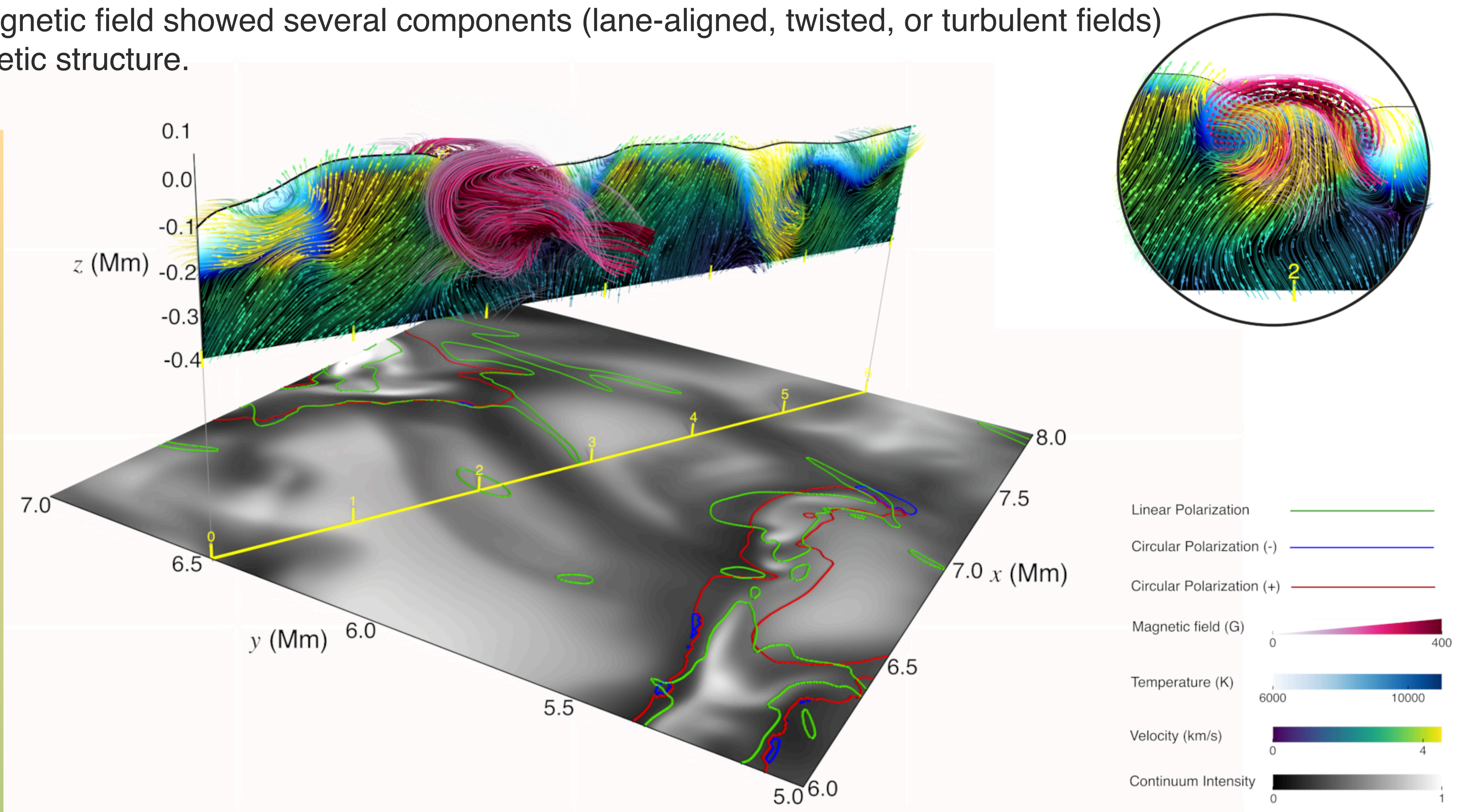
★ Although granular lanes, which are the signature of subsurface vortex tubes, are ubiquitous in the observed continuum figures, we find only in a few cases polarization signal associated with them.

★ We detect in these cases horizontal magnetic field at locations of the dark component of the granular lane.

★ Simulations show how magnetic fields are trapped within horizontal vortex tubes which twist the fields and transport them into the granules where they emerge and are seen as horizontal magnetic field aligned with the granular lanes.

★ Our observations are the first indications of a "shallow recirculation" process taking place on the Sun.

Encouraged by these results, we are confident that future observations at very high spatial resolution and high polarimetric sensitivity will permit us a first glance at the operation of the small-scale dynamo.



The grayscale panel in the bottom part shows the continuum intensity synthesized with NICOLE (Socas-Navarro et al., 2015). The contours in green outline the linear polarisation calculated from the synthesized Stokes profiles. The circular polarization is marked by red and blue contours. The 3D scene above displays the temperature and the flow field below the Rosseland optical depth τ_R = 1 (black curve). The magnetic field lines that cross the section plane are shown in pink color. The circular close-up view provides a clear look at the temperature, flow field, and magnetic field orientation at the location of the granular lane. (Figure from Fischer et al., 2020, the visualization was done with ParaView)

Acknowledgements

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