Rosseland international team
WaLSA: Waves in the Lower Solar Atmosphere at high resolution
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Waves and swirls

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1 Wave conversion: a numerical experiment

Temperature (colors), velocity (arrows), and optical depth $\tau_c = 1$ (dashed curve).

Magnetic field strength (gray scales), level where $c_s = c_A$ (white contour), locations of local wave excitation (crosses).

Movies of wave excitation at $\times_i$, $\times_{ii}$, $\times_{iii}$, and along the lower boundary.

From Nutto et al., 2012 A&A 538, A79.
§ 1 Wave conversion: a numerical experiment (cont.)

Time instant of a spherical, fast acoustic wave, initiated by a local pressure perturbation in the convection zone. When the wave encounters the low beta magnetic flux concentration in the photosphere, it partially converts into a fast magnetic mode, which shows the typical “faning out” already encountered in the 2-D simulation. Colors show absolute velocity perturbation.

Courtesy Christian Nutto, KIS.
1.1 Magnetic halos and shadows

§ 1.1 Magnetic halos and shadows (cont.)

Power maps of the vertical velocity perturbations, $\delta v_z$, taken at 

\[ a) \tau_c = 8 \cdot 10^{-4} \] 

and 

\[ b) \tau_c = 6.7 \cdot 10^{-5} \].

The white contours show the equipartition level $c_s = c_A$. The ellipses mark regions where the magnetic shadow can be identified. Note suppression of power in the region between the large and the small ellipses. From Nutto et al. 2012.

--- toc --- ref ---
1.1 Magnetic halos and shadows (cont.)

a) Broadband continuum at 710 nm. e) Line core intensity of CaI 854.2 nm. b)–d) and f)–h)

Logarithm of the Fourier Doppler-velocity power averaged over the indicated range of frequencies
of the photospheric line Fe I 709.0 nm (b)–d)) and the chromospheric line Ca II 854.2 nm (f)–h)).

From Vecchio, Cauzzi, Reardon et al. (2007), A&A 461, L1. obtained with IBIS at DST.

--- toc --- ref ---------------
Sketch of the three different magneto-acoustic modes that lead to the phenomenon of the magnetic shadow and the magnetic halo.
Gravity waves occur in the stable stratified (subadiabatic) part of the solar atmosphere, i.e., above the convection zone. Their restoring force is buoyancy. They are excited by convective overshoot into the photosphere.

Schematic of the diagnostic diagram for a particular height in the atmosphere. $\omega_{ac} = c_s/(2H_p)$ is the acoustic cutoff period, $N$ the Brunt-Väisälä frequency. Internal, or gravity waves have frequencies $\omega < N$. 

[Diagram showing the relationship between angular frequency ($\omega$), horizontal wavenumber ($k_h$), and the distinction between acoustic, evanescent, and internal waves.]

\[
\omega = \frac{c_s}{2H_p} \quad \omega = \sqrt{gk}
\]

\[\omega_{ac} = \frac{c_s}{2H_p}\]

\[1/(2H_p) \quad k_h^2 > 0\]

\[k_z^2 < 0\]

\[\omega < N\]
Simulation of convective overshoot into the stable stratified photosphere. The simulation domain is $38.4 \times 38.4 \times 2.8 \text{ Mm}^3$ and runs for 8 h physical time. From Vigeesh et al., 2017.
§ 2 Gravity waves (cont.)

Synthetic $v_z - v_z$ phase difference spectra between heights of (a) $z = 100$ km and $z = 140$ km, and (b) $z = 560$ km and $z = 600$ km, for the non-magnetic model ($v_0$) and the magnetic models ($v_{10}$, $v_{50}$, $v_{100}$). Note the absence of upwardly propagating gravity waves in the upper layers of the models $v_{50}$ and $v_{100}$. From Vigeesh et al., 2019.
Vertical mechanical flux spectrum at a height of (a) $z = 360$ km and (b) $z = 700$ km for the nonmagnetic model ($v_0$) and the three magnetic models ($v_{10}$, $v_{50}$, $v_{100}$). Note downwardly propagating mechanical flux in the gravity wave regime in the upper layers of models $v_{50}$ and $v_{100}$. From Vigeesh et al., 2019.

$$F_M(k, \omega) = \frac{1}{2} C_{p',v}(k, \omega) = \frac{1}{2} \text{Re}\{p'(k, \omega)v(k, \omega)\}$$
Possible explanations for the absence of propagating internal waves in the upper atmosphere of the magnetic simulation are:

- *Mode conversion* of the internal wave to *Alfvénic waves* (unlikely in the present case because to the predominant vertically directed magnetic field);

- Mode coupling to magneto-acoustic waves and *reflection* back into the atmosphere as described by Newington & Cally (2010, 2011).

- Non-linear interaction of internal waves with shear flows, leading to the *breaking of internal waves into turbulence*. (shear flows are provided by swirling motion in the upper atmosphere induced by the magnetic field)
Vorticity $\omega = \nabla \times \mathbf{v}$ is the standard quantity to study vortical flows in fluid dynamics. However, vorticity does not distinguish a shear flow from an actual vortex. To isolate vortices, Zhou et al. (1999) suggest to use the velocity gradient tensor

$$D_{ij} = \partial_j v_i \iff D = \begin{bmatrix} \partial_x v_x & \partial_y v_x & \partial_z v_x \\ \partial_x v_y & \partial_y v_y & \partial_z v_y \\ \partial_x v_z & \partial_y v_z & \partial_z v_z \end{bmatrix}.$$ 

$\omega$ corresponds to the antisymmetrized version of $D$; $D - D^T$. 
It can be shown that $D$ can be decomposed in the following form:

$$
D = \left( u_r, u_{cr}, u_{ci} \right) \begin{bmatrix}
\lambda_r & 0 & 0 \\
0 & \lambda_{cr} & \lambda_{ci} \\
0 & -\lambda_{ci} & \lambda_{cr}
\end{bmatrix} (u_r, u_{cr}, u_{ci})^{-1}
$$

$$
= \left( u_r, u_+, u_- \right) \begin{bmatrix}
\lambda_r & 0 & 0 \\
0 & \lambda_+ & 0 \\
0 & 0 & \lambda_-
\end{bmatrix} (u_r, u_+, u_-)^{-1},
$$

where $u_+ = \frac{1}{\sqrt{2}}(u_{cr} + iu_{ci})$, $u_- = \frac{1}{\sqrt{2}}(u_{cr} - iu_{ci})$,

and $\lambda_+ = \frac{1}{\sqrt{2}}(\lambda_{cr} + i\lambda_{ci})$, $\lambda_- = \frac{1}{\sqrt{2}}(\lambda_{cr} - i\lambda_{ci})$.

$\sqrt{2}\lambda_{ci} \equiv \lambda$ measures the *swirling strength* of the rotative flow, where $4\pi/\lambda = T$ is the period of the rotation and $u_r$ is the rotation axis.
§ 3 Swirls in the solar atmosphere (cont.)

Swirling strength with iso-surface $\tau = 1$ (white) and iso-surface $\beta = 1$ (red).
§ 3 Swirls in the solar atmosphere (cont.)

Swirling strength of a magnetic field-free simulation for comparison.

From Bossart, A., 2018, IRSOL internal report.
Particle tracks. Color range indicates time, starting with blue and turning red with age.

From Bossart, A., 2018, IRSOL internal report.
3 Swirls in the solar atmosphere (cont.)

Identations in magnetic flux concentrations: a source of swirls?

$B_z$ 100 km below $\tau=1$ (background). Vertically directed swirls at same height (blue) and 50 km higher up (green) and overlaps (red). From Bossart, A., 2018.

Interaction of a magnetic flux element (red) with convective flows (blue) resulting in a distortion of the flux tube and generation of transverse motions inside it (green arrows), which create Alfvén waves that propagate into the upper atmosphere. From van Ballegooijen et al. 2011, ApJ 736:3.
§ 3 Swirls in the solar atmosphere (cont.)

Swirling strength (green) over magnetic field strength (reddish) in the photosphere (left) and the chromosphere (right).
§ 3 Swirls in the solar atmosphere (cont.)

Time instant of the velocity field projected into the horizontal plane at 1300 km above \( \langle \tau_c \rangle = 1 \). Overplotted in gray scale is \( \log |B| \) from 1 to 100 G.

Snapshot from simulation v50, which started with a homogeneous, vertical magnetic field of 50 G. From Steiner & Rezaei, 2012.
Patchy appearance of the rate of the vertical and magnetic component of the swirling strength hints at considerable substructure of swirls within magnetic flux concentrations. From Canivete Cuissa, J.-R., 2019, IRSOL internal report.
§ 4 Discovering MHD fine structure of faculae with DKIST

Speckle reconstructed image of facular region taken with the 1 m Swedish Solar Telescope in the continuum at 487.5 nm. Field of view approximately $80'' \times 80''$.

From Hirzberger & Wiehr (2005), A&A 438, 1059
4 Discovering MHD fine structure of faculae with DKIST (cont.)

Temporal variability of facular magnetic field. Swaying flux tube?

*De Pontieu et al. (2006), ApJ 646, 1405*

Faulae provide us with the unique opportunity to see footpoints of fluxtubes from the side!
Temperature perturbation induced by propagating MHD waves initiated through a transversal displacement at the base of the magnetic flux concentration. 

\[ \delta T(t) \]
\[ \delta v_{\parallel}(t) \]
\[ \delta v_{\perp}(t) \]

### 4.1 Instrument set-up

<table>
<thead>
<tr>
<th>Instrument</th>
<th>FOV</th>
<th>channel</th>
<th>$\lambda$ [nm]</th>
<th>cadence</th>
<th>sensitivity</th>
<th>comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>VBI</td>
<td>$45'' \times 45''$</td>
<td>G-band</td>
<td>430.52</td>
<td>3.2 s</td>
<td>S/N = 209</td>
<td>S/N = 209 $\Rightarrow \delta T = 10$ K</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$t_{\text{exp}} = 0.5$ ms</td>
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<tr>
<td>VTF</td>
<td>$60'' \times 60''$</td>
<td>Fe I</td>
<td>630.25</td>
<td>21 s</td>
<td>P/I = $10^{-3}$</td>
<td>6 accumulations, 2 x 2 binning, 11 scan steps, $\Delta \lambda = 3.15$ pm</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>$60'' \times 60''$</td>
<td>Ca II</td>
<td>854.21</td>
<td>1.87 s</td>
<td>S/N = 178</td>
<td>intensity alone, 1 accumulation, 11 scan steps, $\Delta \lambda = 10.68$ pm, 5 fast scans after every 21 s</td>
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<tr>
<td>ViSP</td>
<td>$2'' \times 75''$</td>
<td>Fe I</td>
<td>525.02</td>
<td>2.5 min</td>
<td>P/I = $10^{-3}$</td>
<td>38 slit positions, $\Delta x = 0.053''$, slit width 0.053'', $t_{\text{exp}} = 3.8$ s</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>524.71</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>NIRSP</td>
<td>$2.4'' \times 1.8''$</td>
<td>Fe I</td>
<td>1565</td>
<td>5 s</td>
<td>P/I = $5 \cdot 10^{-3}$</td>
<td>$\delta B = 100$ G detectable</td>
</tr>
</tbody>
</table>

Foresee to sequentially observe 5 facular targets at $\mu \approx 0.6$, each for 20 min.
4.1 Instrument set-up (cont.)

Field of views of VTF (outermost black frame), VBI (approximately image size), ViSP scan area (white slit across image), and DL-NIRSP (white small frame).
### 5 Current CO5BOLD models at KIS and IRSOL

At KIS, we run five different *stellar atmospheric models*, each once with an initial homogeneous vertical magnetic field of a flux density of 50 G and once without magnetic field but with the same HLLMHD solver.

<table>
<thead>
<tr>
<th>model name</th>
<th>$T_{\text{eff}}$</th>
<th>log $g$</th>
<th>$B_z^\text{init}$</th>
<th>$X \times Y \times Z$ [km$^3$]</th>
<th>$\Delta x,y$</th>
<th>$\Delta z$</th>
<th>$N_x \times N_y \times N_z$</th>
<th>t [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>d3t33g45rs</td>
<td>3300</td>
<td>4.5</td>
<td>0</td>
<td>$2394 \times 2394 \times 1629$</td>
<td>4.5</td>
<td>4.5</td>
<td>$532 \times 532 \times 362$</td>
<td>5.6</td>
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<td>&quot;</td>
<td>&quot;</td>
<td>50</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>2.5</td>
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<td>d3t40g45rs</td>
<td>4000</td>
<td>4.5</td>
<td>0</td>
<td>$4734 \times 4734 \times 1232$</td>
<td>9.0</td>
<td>7.0</td>
<td>$526 \times 526 \times 176$</td>
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<tr>
<td>d3t40g45v50rs</td>
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<td>&quot;</td>
<td>50</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>10.5</td>
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<tr>
<td>d3t40g45v100rs</td>
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<td>&quot;</td>
<td>100</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>10.5</td>
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<tr>
<td>d3t50g45rs</td>
<td>5000</td>
<td>4.5</td>
<td>0</td>
<td>$4928 \times 4928 \times 2484$</td>
<td>11.0</td>
<td>9.0</td>
<td>$448 \times 448 \times 276$</td>
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<td>50</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>10.5</td>
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<tr>
<td>d3t50g45v100rs</td>
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<td>&quot;</td>
<td>100</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>10.5</td>
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<tr>
<td>d3gt57g44rs</td>
<td>5770</td>
<td>4.44</td>
<td>0</td>
<td>$5600 \times 5600 \times 2256$</td>
<td>14.0</td>
<td>12.0</td>
<td>$400 \times 400 \times 188$</td>
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<tr>
<td>d3gt57g44v50rs</td>
<td>&quot;</td>
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<td>50</td>
<td>&quot;</td>
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<td>d3gt57g44v100rs</td>
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<td>&quot;</td>
<td>100</td>
<td>&quot;</td>
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<td>&quot;</td>
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<td>10.5</td>
</tr>
<tr>
<td>d3t65g45rs</td>
<td>6500</td>
<td>4.5</td>
<td>0</td>
<td>$8388 \times 8388 \times 4020$</td>
<td>18.0</td>
<td>15.0</td>
<td>$466 \times 466 \times 268$</td>
<td>10.5</td>
</tr>
<tr>
<td>d3t65g45v50rs</td>
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<td>&quot;</td>
<td>50</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>10.5</td>
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<tr>
<td>d3t65g45v100rs</td>
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<td>&quot;</td>
<td>100</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>&quot;</td>
<td>10.5</td>
</tr>
</tbody>
</table>
§ 5 Current CO5BOLD models at KIS and IRSOL (cont.)

From Salhab et al. (2017)
Also at KIS, G. Vigeesh is running a model of large surface area of $38.4 \times \, 38.4 \, \text{Mm}^2$, with and without magnetic field.

<table>
<thead>
<tr>
<th>model name</th>
<th>$T_{\text{eff}}$</th>
<th>$\log g$</th>
<th>$B_z^{\text{init}}$</th>
<th>$X \times Y \times Z , [\text{km}^3]$</th>
<th>$\Delta x, y$</th>
<th>$\Delta z$</th>
<th>$N_x \times N_y \times N_z$</th>
<th>$t , [\text{h}]$</th>
</tr>
</thead>
<tbody>
<tr>
<td>d3t57g45gv</td>
<td>5770</td>
<td>4.44</td>
<td>0</td>
<td>$38,400 \times 38,400 \times 2800$</td>
<td>80</td>
<td>20-50</td>
<td>$480 \times 480 \times 120$</td>
<td>8.0</td>
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<tr>
<td>d3t57g45v10gv</td>
<td>&quot;&quot;</td>
<td>10</td>
<td>&quot;&quot;</td>
<td>&quot;&quot;</td>
<td>&quot;&quot;</td>
<td>&quot;&quot;</td>
<td>&quot;&quot;</td>
<td>8.0</td>
</tr>
<tr>
<td>d3t57g45v50gv</td>
<td>&quot;&quot;</td>
<td>50</td>
<td>&quot;&quot;</td>
<td>&quot;&quot;</td>
<td>&quot;&quot;</td>
<td>&quot;&quot;</td>
<td>&quot;&quot;</td>
<td>8.0</td>
</tr>
<tr>
<td>d3t57g45v100gv</td>
<td>&quot;&quot;</td>
<td>100</td>
<td>&quot;&quot;</td>
<td>&quot;&quot;</td>
<td>&quot;&quot;</td>
<td>&quot;&quot;</td>
<td>&quot;&quot;</td>
<td>8.0</td>
</tr>
</tbody>
</table>
Vigeesh uses these models for studying *gravity waves*, in particular the differences in the propagation of gravity waves between the magnetic and the non-magnetic model.
2. Current CO5BOLD models at KIS and IRSOL (cont.)

At IRSOL, Flavio Calvo is running high resolution solar models (grid size 10 km) with and without magnetic field and various initial field configurations.

<table>
<thead>
<tr>
<th>model name</th>
<th>$T_{\text{eff}}$</th>
<th>$\log g$</th>
<th>$X \times Y \times Z$ [km$^3$]</th>
<th>$\Delta_{x,y}$</th>
<th>$\Delta_z$</th>
<th>$N_x \times N_y \times N_z$</th>
<th>$t$ [h]</th>
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<td>5770</td>
<td>4.44</td>
<td>$9600 \times 9600 \times 2800$</td>
<td>10</td>
<td>10</td>
<td>$960 \times 960 \times 280$</td>
<td>2.0</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>model name</th>
<th>solver</th>
<th>initial magnetic field configuration</th>
<th>$t$ [h]</th>
</tr>
</thead>
<tbody>
<tr>
<td>d3t57g45b0roefc</td>
<td>Roe</td>
<td>no magnetic field</td>
<td>2.0</td>
</tr>
<tr>
<td>d3t57g45b0fc</td>
<td>HLLMHD</td>
<td>no magnetic field</td>
<td>2.0</td>
</tr>
<tr>
<td>d3t57g45v50fc</td>
<td>HLLMHD</td>
<td>vertical, homogeneous, 50 G</td>
<td>2.0</td>
</tr>
<tr>
<td>d3t57g45v200fc</td>
<td>HLLMHD</td>
<td>vertical, homogeneous, 200 G</td>
<td>2.0</td>
</tr>
<tr>
<td>d3t57g45v50fc</td>
<td>HLLMHD</td>
<td>horizontally inflowing, 50 G</td>
<td>2.0</td>
</tr>
<tr>
<td>d3t57g45p200fc</td>
<td>HLLMHD</td>
<td>potential filed configuration</td>
<td>2.0</td>
</tr>
</tbody>
</table>

He uses these models for 

i) statistical properties of “non-magnetic bright points”,

ii) a study of Stokes-$V$ line ratios, and

iii) for the computation of the center-to-limb variation of the continuum polarization.
Solar model, magnetic field-free, 9.6 x 9.6 Mm

$\nu_z$ at $\langle \tau \rangle = 1 = z = 0$

$T (z=1200 \text{ km})$

$\nu_{\text{hor}} (z=1200 \text{ km})$
Piz Daint is a Cray XC50/XC40 with nodes of 12 cores with 64GB RAM and nodes with 18 cores and 128GB RAM, both Intel® Xeon® E5.
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