Numerical simulations in solar physics — comparing synthetic with real observations

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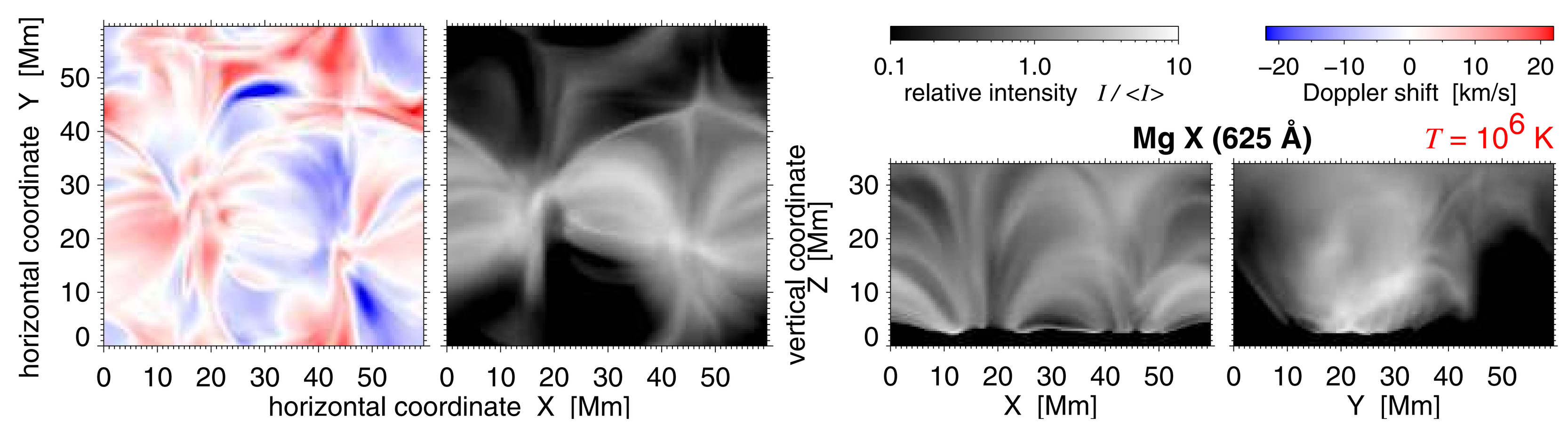
Motivation

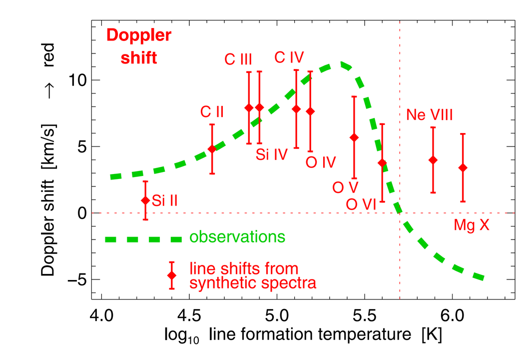
Numerical simulations play an increasingly important role in the interpretation of observational data. The aim is to simulate solar physical processes to a *high degree of realism*, so that the results obtained by means of *"numerical experiments"* – the *"virtual observation"* – can be directly compared to actual observations. This comparison enables us to understand the variety of solar physical phenomena and their relation with each other, and provides information on regions and processes on the Sun that are not accessible to direct observations. Four exemplary comparisons between observations and simulations are shown in this poster.

Corona

Ab initio *three-dimensional magnetohydrodynamic simulations* of the outer solar atmosphere are carried out, where the corona is heated by ohmic dissipation of current sheets that occur through braiding of magnetic flux due to photospheric foot-point motions. We synthesize spectra and filtergrams from the simulation and find that the general appearance of the synthesized corona as well as average Doppler shifts or differential emission measures are very similar to the real solar corona. The persistent *redshifts in the transition region*, which have puzzled theorists since their discovery, are a consequence of flows induced by ohmic heating according to these simulations.



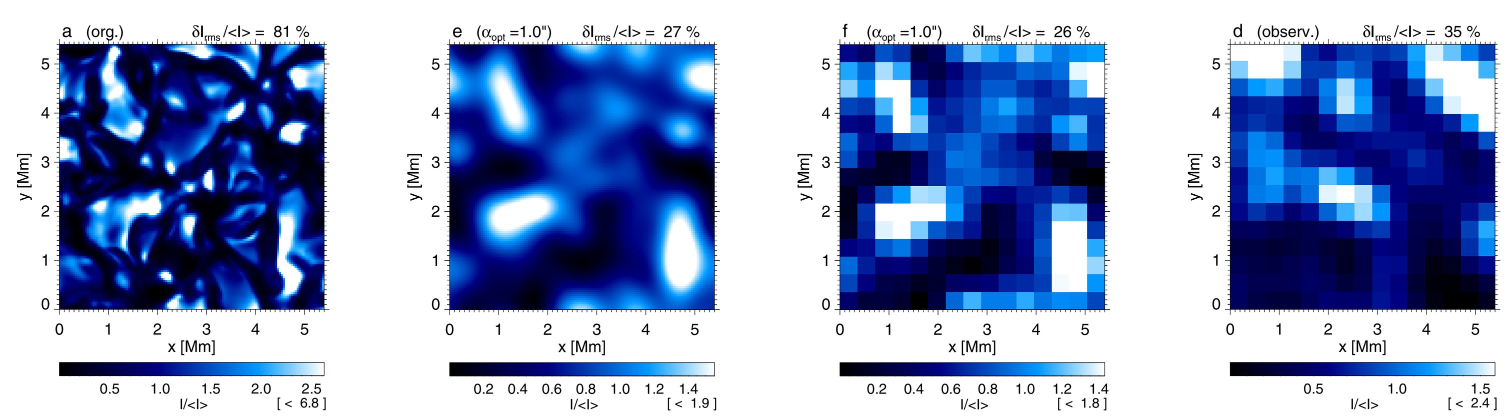
Synthetic Doppler map and intensity map in the line of Mg X (625 Å) formed at about 10^6 K, for a still of the MHD simulation. The two panels to the *left* show the Doppler shift of the synthesized spectra as seen from straight above (colored panel) and the intensity of the respective line (grey-scale panel). This corresponds to the appearance near disk center. The two panels to the *right* show side views of the computational box along the x- and y-axis in line intensity, which resembles the appearance at the limb. The intensities I are scaled with respect to the average (median) intensity $\langle I \rangle$ of the respective map.



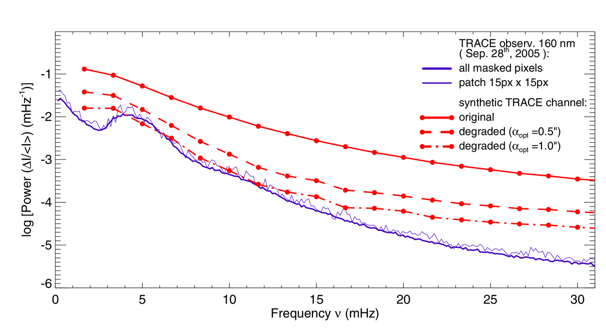
Comparison of *synthesized and observed Doppler shifts*. The diamonds show the Doppler shifts of the average synthetic spectra, the bars indicate the standard deviation of the Doppler shifts of a spatial map as seen looking straight down on the computational box. The lines are ordered according to the formation temperature as follows from the contribution to the emission. The thick dashed line shows the trend as found in observations.

References: Peter H., Gudiksen B., Nordlund, Å. (2004): ApJ 617, L85-L88; Peter H., Gudiksen B., Nordlund, Å. (2006): ApJ 638, 1086-1100

From the chromosphere to the convection zone



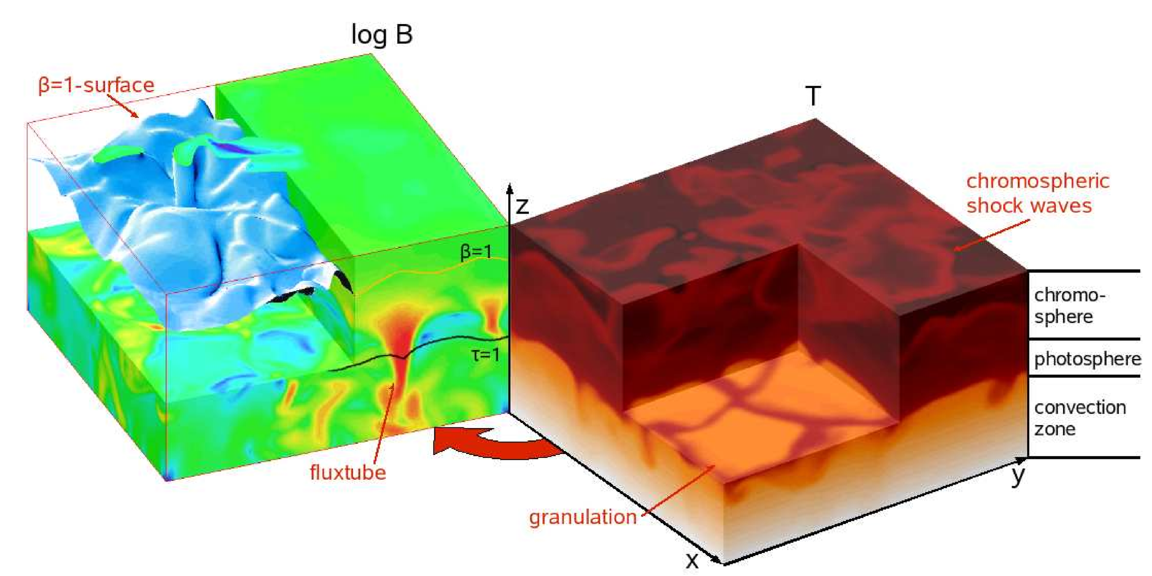
Synthetic intensity images for the *160 nm passband of the TRACE satellite: a)* image at full resolution, *e)* degraded to a spatial resolution of 1.0″, and *f)* after integration on TRACE 0.5″ pixels. Panel *d)* shows *observed* TRACE data from September 28, 2005, taken from a data set kindly provided by Fossum & Carlsson. The color scale ranges of the panels are clipped individually. The maximum value is given in brackets.



Average one-sided power spectra for the sequence of *synthetic* TRACE images (red curves) for full spatial resolution (solid) and degradation to 0.5″, and 1.0″ (dot-dashed). The blue curves are from *observational* data. From these results we come to the conclusion that in the internetwork region the acoustic flux provides sufficient energy for heating the solar chromosphere contradicting previous results from one-dimensional modelling that did not take image degradation into account.

References: Wedemeyer-Böhm, S., Steiner, O., Bruls, J., and Rammacher, W.: 2006, in The Physics of Chromospheric Plasmas, astro-ph/0612627

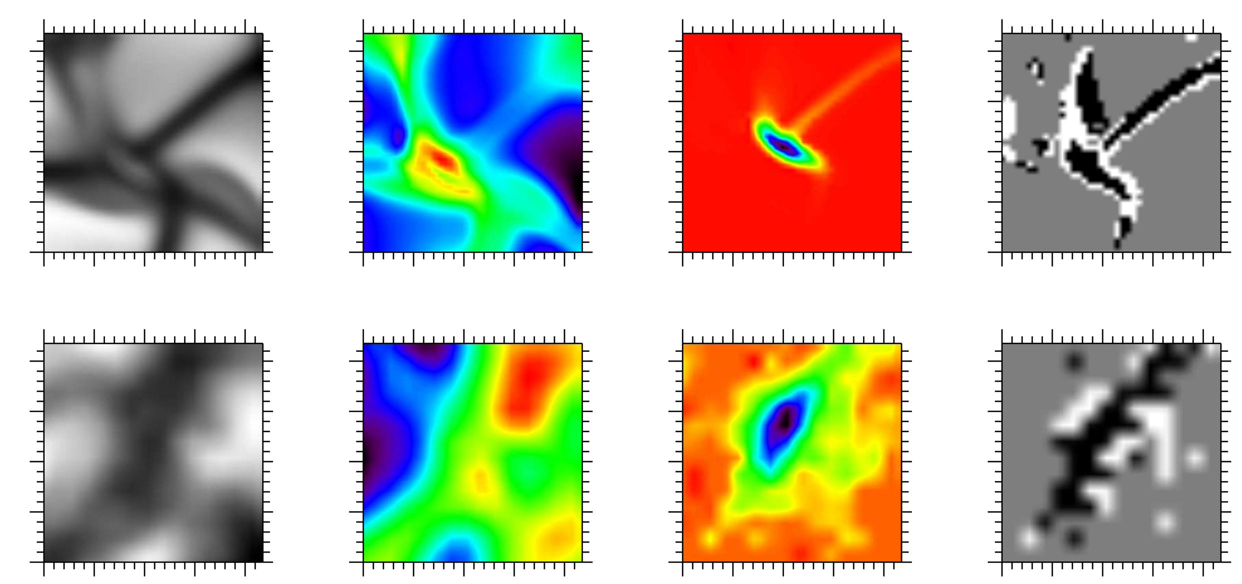
chromosphere



photosphere

Time instant of a *three-dimensional magnetohydrodynamic simulation* of the solar atmosphere encompassing the height range from the top of the convection zone to the mid-chromosphere. *Left:* Magnetic flux density on a color scale, where red signifies strong ($\gtrsim 0.1$ T) and blue weak fields. The surface of equipartition between magnetic and thermal energy density ($\beta = 1$) is indicated as blue surface (on the lateral boundaries by a yellow curve). The black curve indicates optical depth unity. *Right:* The temperature in colors shows granules and cool intergranular downflows at a height that corresponds to the mean optical depth unity. The chromosphere consists of a *mesh-work like pattern of hot shock waves*.

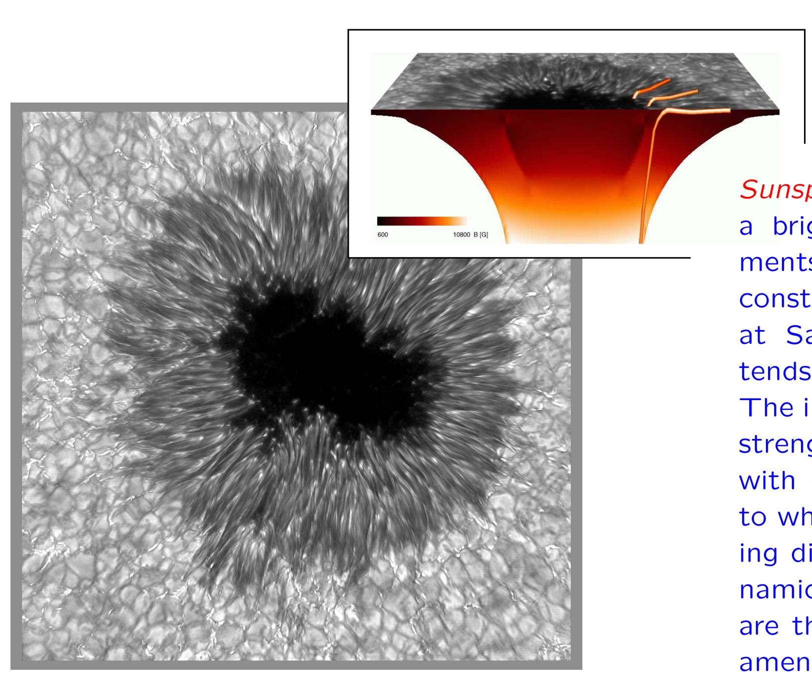
References: Wedemeyer-Böhm, S.: 2007, IAU Symposium 239



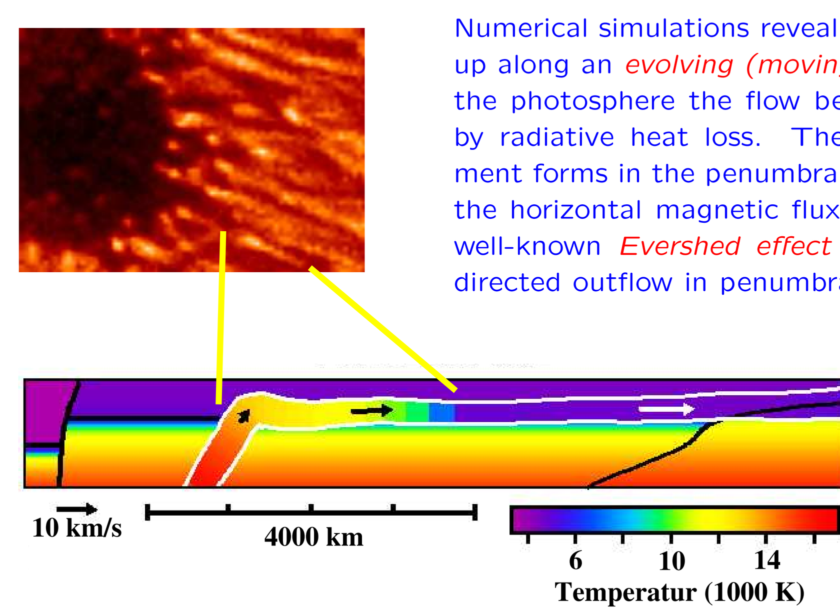
Top panels: *Synthetic* maps from 3-D simulation. *Bottom* panels: Corresponding *observations* with the *SOT-telescope* on board of the Japanese *HINODE space mission*. The panels show from left to right the continuum intensity at 630 nm, where granules are visible, the Doppler shift, the magnetographic signal, and the sign of the Stokes-V area asymmetry, δA. Here, we can for the first time observationally confirm the prediction from simulations that magnetic flux concentrations tend to have negative (black) area asymmetry in the central part while $\delta A > 0$ prevails in the peripheral region. Minor tick marks indicate 0.1″ spatial distance.

References: Rezaei, R., Steiner, O., Wedemeyer-Böhm, S., Schlichenmaier, R., and Lites, B.W.: 2007, A&A in prep.

Sunspots

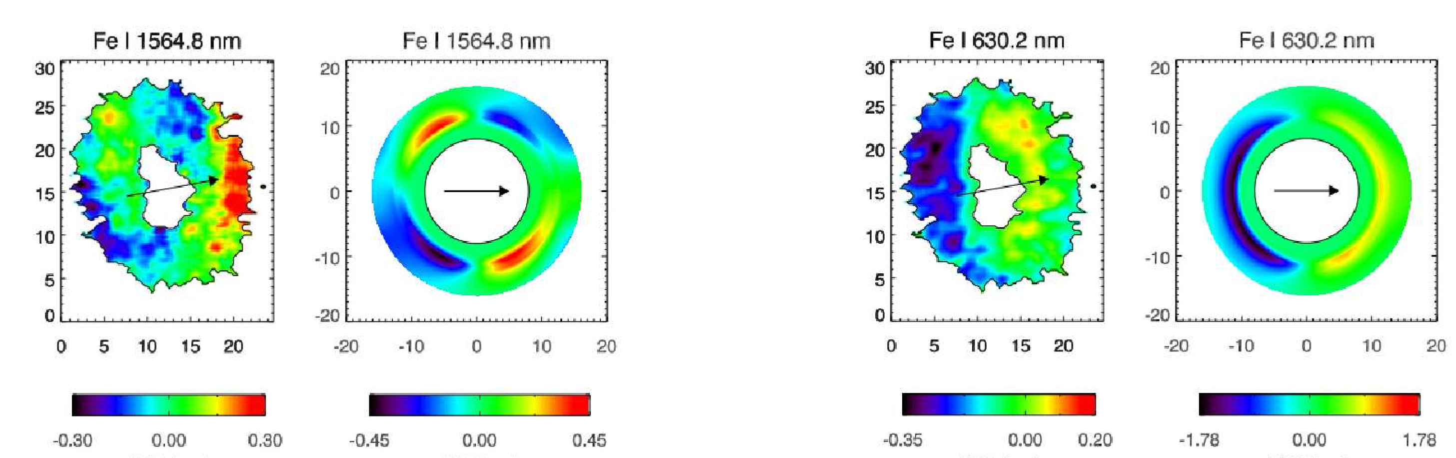


Sunspots consist of a dark umbra and a brighter ring of radially aligned filaments, the *penumbra*. The speckle reconstructed image, taken with the DST at Sacramento Peak Observatory, extends 40 000 km in each direction.
The inset displays a *sunspot model:* The strength of the magnetic field increases with depth (color coded from dark red to white) and forms a funnel of decreasing diameter with increasing depth. Dynamically evolving magnetic flux tubes are thought to cause the penumbral filamentation.



Numerical simulations reveal that a hot up-flow builds up along an *evolving (moving) magnetic flux tube*. In the photosphere the flow bends horizontal and cools by radiative heat loss. Thereby a bright radial filament forms in the penumbra. The outward flow along the horizontal magnetic flux tube corresponds to the well-known *Evershed effect* — a horizontal, radially directed outflow in penumbrae.

References: Schlichenmaier, R., Jahn, K., and Schmidt, H.U.: 1998, A&A 337, 897-910
Schlichenmaier, R., Jahn, K., and Schmidt, H.U.: 1998, ApJ 493, L121-L124



A conspicuous property of penumbrae is the asymmetry of their spectral line profiles. In the moving tube model these arise from discontinuities in velocity along a line of sight. The asymmetry of Stokes-V profiles can be quantified by the net circular polarization, $N = \int V(\lambda)\,\mathrm{d}\lambda$. Maps of N in two different spectral lines are shown. For each line, the map to the left is *observed* (with TIP & POLIS at the VTT), while the map to the right follows from *line synthesis* of the moving tube simulation. The agreement is remarkably good, demonstrating that the moving tube model is a realistic description of the penumbra.

References: Müller, D.A.N., Schlichenmaier, R., Fritz, G., and Beck, C.: A&A 460, 925-933
Müller, D.A.N., Schlichenmaier, R., Steiner, O., Stix, M.: A&A 393, 305-319