High-resolution modeling of the solar photosphere with the ANTARES RHD-code

Investigation of rotating intergranular plasma jets

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Abstract

Small granules that do not originate from the fragmentation process of regular sized granular cells and evolve on a considerably shorter timescale populate the intergranular lane. They are found in high-resolution observational and hydrodynamic simulation data of the quiet sun's photosphere. We study their topology and dynamics based on a segmentation algorithm. The flow field suggests that they represent high-vortical jet-like structures that are found to differentially rotate about their center axis. Their associated high horizontal kinetic energy flux exceeds that of regular granules and may excite significant Poynting flux through MHD kink waves and torsional Alfvén waves that would be high enough to effectively heat the chromosphere and corona if only 10% of the wave energy is assumed to be dissipated into heat.

Introduction

We study the structure and dynamics of the solar photosphere from radiation hydrodynamics (RHD) modeling. The high resolution of our photospheric model allows us to examine small-scale convective structures that do not originate from the fragmentation of larger granular cells but form and dissolve in the intergranular lanes on timescales well below the lifetime of typical granulation cells. Many such integranular structures are associated with strong vortex motions as have been detected in numerous observations e.g. [8, 1, 9] and simulations alike e.g. [12, 7]. 3-D radiative MHD simulations showed that convective overturning and Kelvin-Helmholtz instabilities give rise to such small-scale vortices [2], which themselves can trigger acoustic wave excitation or the spontaneous formation of magnetic pore structures.

Numerical Model & Methods

The study is based on a simulation of the solar near-surface convection using the code `ANTARES` (A Numerical Tool for Astrophysical RESearch) [4]. It considers **full radiative transfer** and realistic microphysics as well as realistic opacities based on the opacity distribution functions of the ATLAS-9 package to determine bin-averaged opacities and source functions.

- The radiative transfer equation is solved in the upper region of $\sim 1\,\mathrm{Mm}$ extent using non-gray opacities with 4 bins.
- The temporal integration is performed with a second or third order Runge-Kutta scheme with **weighted essentially non-oscillatory (WENO) finite volume schemes**.
- The applied high resolution finite-volume method is capable of treating turbulence by adopting **local mesh refinement**.
- Boundary conditions: Originally closed boundary conditions prone to non-physical reflections of waves and shocks are now replaced by open boundary conditions at the top and bottom, thereby allowing for convective mass and energy in- and outflows. In horizontal direction periodic boundary conditions are applied.
- Initial conditions: Temperature values are set to 4350 K and 20 000 K at the top and bottom of the grid. The horizontal momentum densities ϱv and ϱw are slightly distrubed before the system is evolved in time.
- The lattice extent is $18\,\mathrm{Mm} \times 18\,\mathrm{Mm}$ in horizontal and 4.5 Mm in vertical direction, featuring a grid resolution of $\Delta y = \Delta z = 35\,\mathrm{km}$ and $\Delta x = 11\,\mathrm{km}$.

For the study of the structure and dynamics of intergranular jets, the 3-D segmentation algorithm developed by Lemmerer et al. 2014 [3] has been applied: Starting at the highest vertical position of a granule the maximum upflow velocities are traced on each level of the 3-D segment. The size of the segment is compared to the size of the segment in the underlying layer. If it exceeds a certain threshold, morphological operations are applied.

Preliminary Results

Several case studies of intergranular small granules up to a height of 600 km have been performed. In vertical direction they have a tube-like topology in contrast to the divergent flow field of regular granules and reach far below the visible surface.

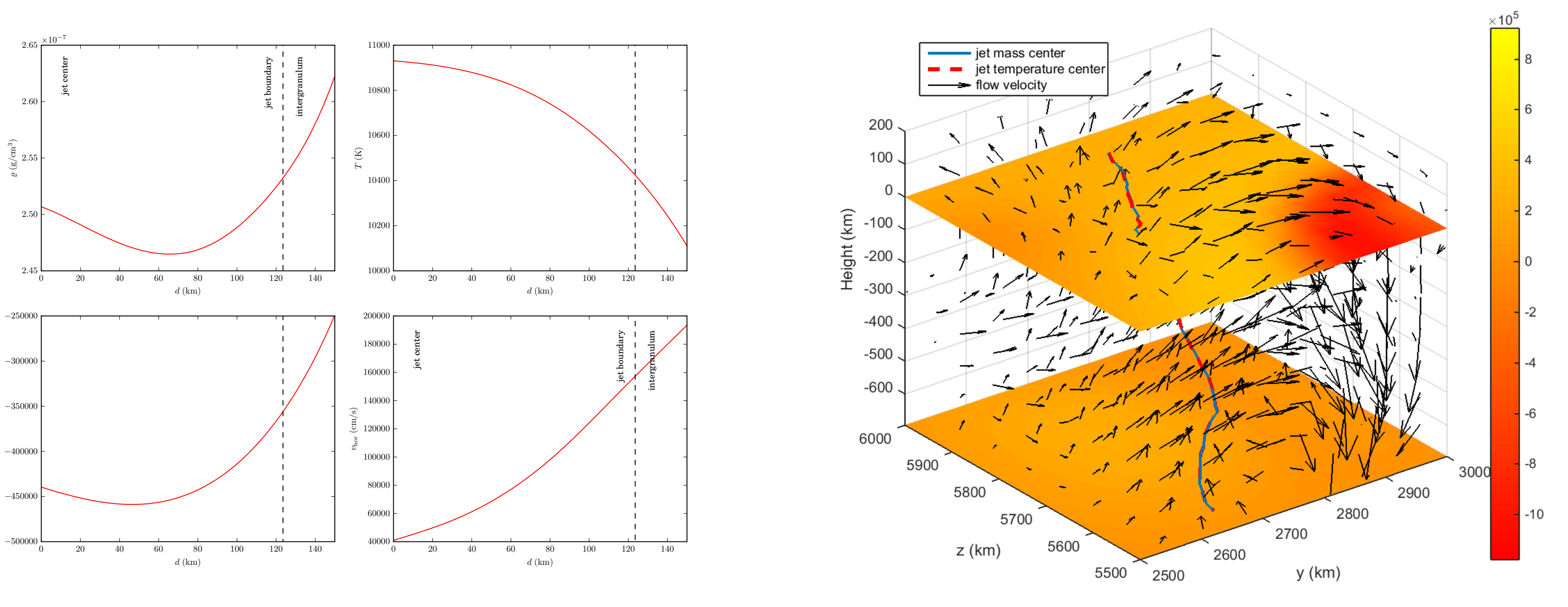

Figure 1: Horizontal gas density-, temperature- and velocity profiles of an intergranular jet evaluated 150 km below the surface. (*left*). Flow field around the jets vertical center (*right*). The mass- and temperature centers almost coincide along the whole vertical structure, while the maximum upflow, $\min(u)$, is dislocated from the center.

- Typical lifetimes do not exceed 1.5 min.
- Considerably larger upflow velocities as compared to regular sized granules are found. Upflows are highest, $u \approx -2.5\,\mathrm{km/s}$, about 150 km below the surface.
- High vortical flows were found within the boundaries of the intergranular upflows.
- Tracing of streamlines reveals a differential rotation of the structure as a whole.
- An increased horizontal kinetic energy flux as compared to regular granules has been found below the surface. Above the surface these fluxes are of comparable magnitude and decrease fast with height.

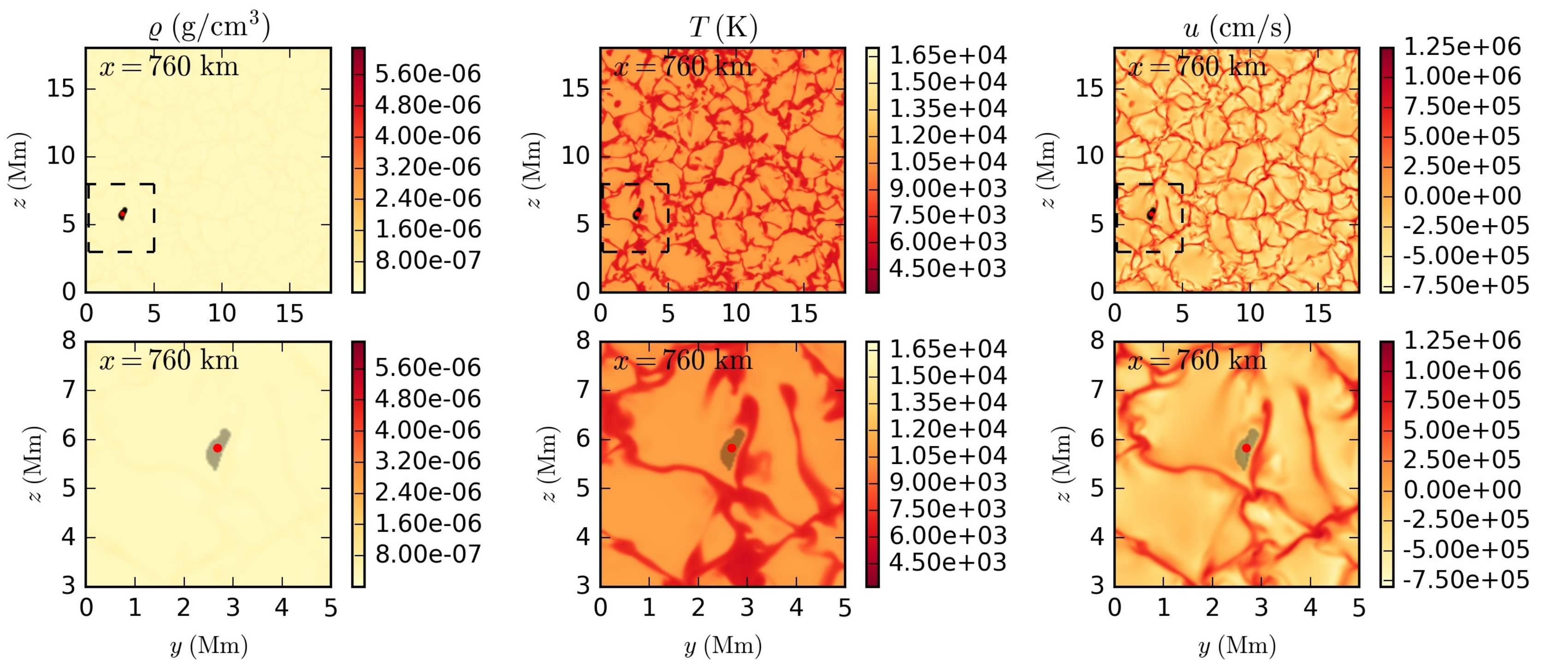

Figure 2: Gas density, temperature and vertical velocity images of the full grid domain and in the vicinity of the intergranular jet taken 150 km below the surface. The gray shaded area marks the jet's cross section as evaluated from the 3-D segmentation of [3]. The jet's profile strongly deviates from a circular cross section.

Conclusions

- The findings indicate a jet-like character rather than being an exclusively convective phenomenon. They are believed to be triggered by turbulent convection and thus can be studied from RHD modeling of the quiet sun.
- The jets may generate MHD waves in magnetic flux tubes which are anchored in the photosphere. The horizontal motions may excite MHD kink waves [6, 11] or torsional Alfvén waves [5, 10], which transport photospheric energy into upper layers.
- If only 1% of the horizontal kinetic energy flux associated with the intergranular jets is transferred into MHD waves, the wave energy flux is sufficiently high to compensate energy losses from the quiet sun chromosphere and to heat the corona.

Forthcoming Research

For a quantitative description of the Poynting flux associated with intergranular vortex jets MHD simulations are inevitable. For this reason this study is soon to be complemented by an MHD upgrade of `ANTARES`, such that the influence of the magnetic field on the photospheric dynamics can be further examined.

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