Realistic Modeling of Interaction of Quiet-Sun Magnetic Fields with the Chromosphere

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High-resolution observations and 3D MHD simulations reveal intense interaction between the convection zone dynamics and the solar atmosphere on subarcsecond scales. To investigate processes of the dynamical coupling and energy exchange between the subsurface layers and the chromosphere we perform 3D radiative MHD modeling for a computational domain that includes the upper convection zone and the chromosphere, and investigate the structure and dynamics for different intensity of the photospheric magnetic flux. For comparison with observations, the simulation models have been used to calculate synthetic Stokes profiles of various spectral lines. The results show intense energy exchange through small-scale magnetized vortex tubes rooted below the photosphere, which provide extra heating of the chromosphere, initiate shock waves, and small-scale eruptions.

**‘StellarBox’ code (A. Wray)**

- 3D rectangular geometry
- Fully conservative compressible MHD
- Fully coupled radiation solver:
- LTE using 4 opacity distribution-function bins
- Ray-tracing transport by Beezian method
- 18 ray (2 vertical, 16 slanted) angular quadrature
- Non-ideal (tabular) EOS
- 4th order Pade spatial derivatives
- 4th order Runge-Kutta in time
- LES-Eddy Simulation options (turbulence models):
  - Compressible Dynamic Smagorinsky model (Germano et al., 1991)
  - MHD subgrid models (Balasuriya et al., 2010)
- DNS-Hyperviscosity approach

**Basic equations**

The equations we solve are the grid-cell averaged

Conservation of mass:
\[
\frac{\partial \rho}{\partial t} + \nabla \cdot (\rho \mathbf{u}) = 0
\]

Conservation of energy:
\[
\frac{\partial \rho E}{\partial t} + \nabla \cdot (\rho \mathbf{u} E + \mathbf{u} \cdot \mathbf{F}) = -\rho \mathbf{u} \cdot \mathbf{u} + \mathbf{u} \cdot \mathbf{F}
\]

Conservation of magnetic flux:
\[
\frac{\partial \mathbf{B}}{\partial t} + \nabla \times (\mathbf{u} \times \mathbf{B}) - \frac{1}{\rho} \mathbf{F} = 0
\]

**Non-ideal (tabular) EOS**

**Fully conservative compressible MHD**

**3D rectangular geometry**

**DNS-Hyperviscosity approach**

**Topological structure of electric current density below and above the photosphere. Streamlines correspond to electric currents originating from positive (orange) and negative (blue) polarity patches. The semi-transparent horizontal plane shows the vertical magnetic field distribution in the photosphere, where blue indicates negative polarity and red positive polarity.**

**Time series with 15s cadence of temperature (a), vertical velocity (b), and density (c) at a height of 625 km above the solar surface.**

**Comparison of contributions to flow ejection of hydrodynamic (red curves) and magnetic (Lorentz force, blue curves) vertical accelerations (normalized by the gravitational acceleration) at two altitudes: 780km & 300km above the photosphere. Dashed curves show the vertical velocity, \(V_z\), given for reference at the same layers.**

**Mean vertical profiles of the unsigned magnetic field components. Error bars correspond to the rms of fluctuations.**

**Horizontal snapshot of a section of the computational domain in the photosphere for: a) vertical velocity; b) magnetic field strength; c) vertical component of the electric current density; d) logarithm of the turbulent magnetic Prandtl number; e) turbulent magnetic diffusivity; and f) time-derivative of the magnetic energy density.**

**Formation of magnetic patches by turbulent dynamo action from an initial 10¹⁴ G random seed field. The blue-red color scale corresponds to vertical magnetic field strength from -300 to 300 G at the photosphere layer. A typical size of the magnetic structures is 150 to 300 km.**

**Conclusions**

High-resolution observations reveal intense and dynamic interactions between the surface layers and the low atmosphere in quiet-Sun regions with relatively weak mean magnetic field. Radiative MHD simulations can reproduce many features of the observed phenomena and provide an important complementary tool for investigation of the underlying physical processes. According to our numerical simulations the local dynamo process is responsible for the quiet-Sun magnetic field. It operates in the near-surface layers and provides Poynting flux sufficient to heat the chromosphere and corona. Spontaneous and ubiquitous flows eruptions occur everywhere in the quiet Sun. These eruptions are driven by impulsive increases in pressure gradient due to turbulent motions associated with vortex tubes. The plasma flow in the eruptions is accelerated by the Lorentz force in higher (mid-chromospheric) layers from 6 to 12-15 km/s. Our simulations demonstrate that shock generation in the chromosphere can be due to spontaneous vortex tube dynamics.