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.

**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 momentum:

\[ \frac{\partial}{\partial t} \left( \rho \mathbf{u} \right) + \nabla \cdot (\rho \mathbf{u} \otimes \mathbf{u}) = -\nabla p + \mathbf{F}_{\text{ext}} - \mathbf{F}_{\text{visc}} \]

Conservation of energy:

\[ \frac{\partial}{\partial t} \left( \rho E \right) + \nabla \cdot \left( \rho \mathbf{u} E + \mathbf{u} \cdot \mathbf{F}_{\text{rad}} \right) = \mathbf{u} \cdot \mathbf{F}_{\text{ext}} - \nabla \cdot \mathbf{q} \]

Conservation of magnetic flux:

\[ \frac{\partial}{\partial t} \left( \rho B_\parallel \right) + \nabla \cdot \left( \rho \mathbf{u} B_\parallel \right) = \mathbf{F}_{\text{mag}} \]

**StellarBox** code (A. Wray)

- 3D rectangular geometry
- Fully conservatively compressible MHD
- Fully coupled radiation solver
- LTE using 4 opacity distribution function bins

Ray-tracing transport by Feautrier method
- 18 ray (2 vertical, 16 slanted) angular quadrature
- Non-ideal (tabular) EOS
- 4th order Padé 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 (Balasubramanian et al., 2010)

DNS-Hyperviscosity approach

**Local Dynamo**

- Topology of the magnetic field lines above the photosphere in the local dynamo simulations. The horizontal plane shows the distribution of the vertical magnetic field in the photosphere. Red corresponds to positive polarity and blue to negative polarity of the vertical magnetic field. The range of field strength is from -2000 to 2000 G.

- Formation of magnetic patches by turbulent dynamo action from an initial 10^14 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.

**Ubiquitous small-scale eruptions**

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

**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接地气ly Poynting flux sufficient to heat the chromosphere and corona. Spontaneous and ubiquitous small-scale 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.