Realistic Modeling of Multi-Scale MHD Dynamics of the Solar Atmosphere

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Realistic 3D radiative MHD simulations open new perspectives for understanding the turbulent dynamics of the solar surface, its coupling to the atmosphere, and the physical mechanisms of generation and transport of non-thermal energy. Traditionally, plasma eruptions and wave phenomena in the solar atmosphere are modeled by prescribing artificial driving mechanisms using magnetic or gas pressure forces that might arise from magnetic field emergence or reconnection instabilities. In contrast, our ‘ab initio’ simulations provide a realistic description of solar dynamics naturally driven by solar energy flow. By simulating the upper convection zone and the solar atmosphere, we can investigate in detail the physical processes of turbulent magnetoconvection, generation and amplification of magnetic fields, evolutions of MHD waves, and plasma eruptions. We present recent simulation results of the multi-scale dynamics of quiet-Sun regions, and energetic effects in the atmosphere and compare them with observations. For the comparisons we calculate synthetic spectropolarimetric data to model observational data from SDO, Hinode, and the BBSO New Solar Telescope.

**SolarBox code**
- 3D rectangular geometry
- Fully conservative, Fully compressible
- Fully coupled radiation solver
- 175 using a spatially distribution function time integration
- Beam tracing by Fourier method
- Tg in (2 relations) excited
- Angular spectrum
- Non-linear Euler EOS
- Solar radiative spatial discretization
- Solar Rayleigh-Hufnle time integration
- LES Simulation options (spherenucles)
  - Compressible Magnetoacoustic
  - Compressible Dynamics
  - Magnetic reconnection (MHD)
  - MHD simulations (Ballester et al., 2011)
- MP output file (plane and pencil versions)

**Basic equations**

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

- Conservation of energy:
  \[ \frac{\partial E}{\partial t} + \nabla \cdot (E \mathbf{v} - \mathbf{F}_e) = \mathbf{F}_g + \mathbf{F}_r + \mathbf{F}_m \]

- Conservation of momentum:
  \[ \frac{\partial \mathbf{v}}{\partial t} + \nabla \cdot (\rho \mathbf{v} \mathbf{v} - P \mathbf{I}) = \nabla \cdot \mathbf{F}_m + \mathbf{F}_e - \mathbf{F}_g \]

**Magnetized vortex tubes and flow eruptions**

- Different stages of a flow ejection. Black horizontal line: plasma tube. Translucent horizontal line: fluid layer. Red color corresponds to positive polarity, blue color to negative polarity of the vertical magnetic field. The range of height of the vertical and transverse small-scale magnetic fields.

**Conservation of magnetic flux**

\[ \frac{\partial B}{\partial t} = \nabla \cdot (\mathbf{v} \times \mathbf{B}) = 0 \]

**Topography of the magnetic field lines above the photosphere**

- Topography of the magnetic field lines above the photosphere in sections 0° and 30°. Red color corresponds to positive polarity, blue color to negative polarity of the vertical magnetic field. The range of height of the vertical and transverse small-scale magnetic fields.

**Conclusions**

- The small-scale dynamics are not easily observed in broad-band images even with high observational spatial resolution. We examine four lines (5250 Å, 6173 Å, 6301 Å and 15648 Å) for studying the temporal evolution of the synthetic data to achieve direct comparison of observations and numerical models.

**Modeling center-to-limb variations of the HMI observables**

- Comparison of Stokes I (red) by line for four different lines in the panel and location of the region of sample indicated (bottom).

**Light curves**

- Comparison of the synthetic line profiles to observed data. Left panel: Doppler shift (top) and continuum intensity (bottom) for Fe I (6173 Å, red curves) and Fe II (5250 Å, blue curve). The spectra reveal the line asymmetry, which originate in the photosphere. Some of these can be identified as ultrafine loops above the granulation.

**Local dynamic simulations**

- Time-difference between snapshots is 10 s. White circle shows the location of a probe for studying the evolution of the Stokes profile shape.